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DESIGN CRITERIA FOR DC LINK FILTERS IN A SYNCHRONOUS GENERATOR-PHASE CONTROLLED RECTIFIER-FILTER-LOAD SYSTEM

by

Gregory J. Greseth

June 1999

Thesis Advisor: John G. Ciezki

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Power electronics have advanced to the point that they can be considered for use in large, high power dc electrical distribution systems. The proposed Navy DC Zonal Electrical Distribution System (DC ZEDS) being designed for the new DD-21 utilizes a rectified ac generator output which is filtered and stepped to usable voltages by local dc-dc converters. One characteristic of the high-bandwidth converters is a negative input impedance, which when coupled with an LC input filter, can lead to system instabilities. This thesis examines various stability criteria for determining parameters of the dc link filter. Comparisons between a simplified system model, a model using subsystem impedances and an Advanced Continuous Simulation Language (ACSL) model of a reduced-order system are made. Simulations were conducted to verify the validity of the stability criteria. The ACSL model provides an extremely useful tool in evaluating the response of various system parameters to changes in design values. The design criteria examined in this thesis can be ultimately used to provide design specifications to future vendors.

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ABSTRACT

Power electronics have advanced to the point that they can be considered for use in large, high power dc electrical distribution systems. The proposed Navy DC Zonal Electrical Distribution System (DC ZEDS) being designed for the new DD-21 utilizes a rectified ac generator output which is filtered and stepped to usable voltages by local dc-dc converters. One characteristic of the high-bandwidth converters is a negative input impedance, which when coupled with an LC input filter, can lead to system instabilities. This thesis examines various stability criteria for determining parameters of the dc link filter. Comparisons between a simplified system model, a model using subsystem impedances and an Advanced Continuous Simulation Language (ACSL) model of a reduced-order system are made. Simulations were conducted to verify the validity of the stability criteria. The ACSL model provides an extremely useful tool in evaluating the response of various system parameters to changes in design values. The design criteria examined in this thesis can be ultimately used to provide design specifications to future vendors.

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I. PROJECT BACKGROUND

Many recent issues have evolved which warrant the need and provide the motivation for a new way of thinking about electric power distribution on-board Navy ships. In recent years, the Navy has pushed for more use of Commercial-Off-The-Shelf (COTS) parts in their new ship designs and existing ship upgrades. Hand-in-hand with this trend is the updating and designing of systems using the latest and most advanced technology available on the world market. Budgets are currently limited, which is forcing the need for cost effective designs. As ships are getting more complex, the possibility of automated systems is growing. The move towards automation is also driven by the economics of streamlining the manning of future Navy ships. Naval architecture is experimenting with unique designs which require innovative ship system designs to allow for more flexibility in their arrangements. Currently, the Navy implements a radial distribution configuration for electric power on-board its vessels. A suggested alternate option is that of zonal distribution.

The Direct Current Zonal Electrical Distribution System (DC ZEDS) is a component of the Integrated Power System (IPS) currently being proposed for use on the new DD-21 design. The basic concept for the IPS is to use a common set of prime movers to generate power for both propulsion and distribution. It is fundamentally different from the radial design in many respects. These differences provide numerous advantages as outlined below.

A. RADIAL DISTRIBUTION

The radial electric power distribution concept involves distributing 60 Hz alternating current (ac) power produced by a limited number of generators to loads throughout the ship in a pyramid type configuration. Branching occurs from switchboards which route power to power panels located in the general area of the loads that they supply. Loads which are considered non-vital receive power from a single

source. Loads which are considered vital for ship operation are made more reliable by powering them from two different sources through merging branches of the pyramid. Power panels typically have multiple switchboard inputs. As a result, isolating power to a local area in a ship is unnecessarily complex. Standardization of the electric power distribution system among all ship classes is difficult at best due to the different number of power sources and vital loads.

B. ZONAL DISTRIBUTION

The zonal electric power distribution concept implements two power buses that run lengthwise through the ship in a configuration that, like the shipboard firemain system, maximizes reliability and minimizes the possibility that both buses are affected by a single battle casualty. All operating generators are connected to both buses via switchboards. Individual zones are designated typically to be areas which directly relate to flooding control zones. Localized power isolation would, therefore, be very clear-cut and easily learned during a sailor's shipboard indoctrination period. Operation of a zonal distribution system would also be similar between ship classes.

C. DC ZONAL DISTRIBUTION

DC ZEDS expands upon the zonal distribution concept in the following manner. High voltage (approximately 1100 V) dc is distributed along the main power busses. The Ship's Service Converter Modules (SSCM) are dc-dc converters which buffer the main bus and interzone loads as well as regulate output voltages. Where ac power is required, Ship's Service Inverter Modules (SSIM) are used to convert the dc to ac and regulate the ac voltage and frequency within the zone. Vital loads are connected to both the port and starboard SSCM via a diode auctioneering process. Additional dc-dc converters synthesize the regulated lower dc voltages, for example 155 V and 270 V, required by combat systems.

The advantages of a DC ZED system are numerous. The most significant advantage is increased survivability during casualty situations. SSCMs can be programmed to act as "smart" circuit breakers. This would result in maximizing the ship's capabilities to continue operating available equipment. A study has shown that a second improvement would be weight and space savings from the use of solid-state components and a reduced amount of cabling throughout the ship [1]. The use of a dc system simplifies operations such as paralleling loads. Only voltages need to be matched on a dc system, whereas voltages, frequency, and phase need to be matched on an ac system. A fourth benefit is that variable speed ac motor control is easily realizable with the Ship's Service Inverter Modules (SSIM), which are programmable solid-state dc-ac inverters. Finally, because the operating generators' frequencies are decoupled from the ac loads' operating frequencies, the prime movers can function at their most efficient speeds.

Some disadvantages to DC ZEDS must be acknowledged. The state-of-the-art solid-state switches used in power electronics today still limit the dc bus voltage to between 1500 volts and 2000 volts. Maximizing bus voltage is important in the effort to minimize conduction losses and therefore minimize conductor size. However, higher voltages pose concerns regarding system grounding and proper isolation of the dc-dc converters. An additional disadvantage is that designers need to more intelligently merge the various components within the system due to stability concerns.

D. PREVIOUS DC ZEDS RESEARCH

Several theses from the Naval Postgraduate School have investigated various aspects of DC ZEDS. These areas include modeling portions of the system to observe controllability and stability issues of both dc-dc converters and synchronous generators, as well as building and testing dc-dc converters and controllers [2-14]. Most recently, an investigation of frequency-based load sharing between current-mode-controlled buck

converters was conducted which included an rms frequency estimation algorithm and accompanying hardware to achieve the desired load sharing characteristics [15].

Previous work conducted in the fields of synchronous machine modeling and dc link filter stability issues were used as the foundation for this thesis. Modeling of an uncontrolled synchronous machine in a voltage-behind-reactance representation was conducted by Sudhoff and Wasynczuk [16] and Branson, Ciezki, Sudhoff, and Wasynczuk [17]. Research conducted by Sudhoff, Corzine, and Glover at the University of Missouri-Rolla, and Hegner and Robey at the Naval Surface Warfare Center makes observations on stability conditions in a simplified dc link model [18]. A technical report by Ciezki and Ashton at the Naval Postgraduate School discussed converter and converter control design methodology [19]. A dissertation by Belkhayat explored an impedance-based stability criteria for a stand-alone dc-dc converter [20]. This small-signal requirement was investigated by application of Nyquist stability criteria. Finally, research conducted by Belkhayat and Cooley at the Naval Surface Warfare Center, and Witulski at the University of Arizona investigated large-signal stability criteria for distributed systems with constant power loads [21].

E. THESIS GOALS

This thesis explores various stability criteria for a representative ship-board dc power distribution system that includes a synchronous generator, a phase-controlled rectifier, a LC link filter, and a dc-dc converter. Specific limits on the filter parameters and converter input impedance which can be given as design specifications to contractors are the desired results. The analysis methods examined are a simplified constant-power dc link model, a model based on system impedances, and a Lyapunov-based, large-signal nonlinear representation. All models were studied using the Advanced Continuous Simulation Language (ACSL) together with specially written MATLAB script files. In addition, an ACSL model of the entire system was created for more advanced analysis.

F. CHAPTER OVERVIEW

The derivation of modeling equations for a reduced-order synchronous machine/rectifier drive are detailed in Chapter II. The accompanying model code is then explained in detail. Chapter III examines a simplified dc link model and the limitations placed to ensure stability by the Hurwitz criterion. The results of simulations used to verify the limitations are presented. Chapter IV then examines stability criteria based on a system impedance model. Design of a dc converter is outlined, the required impedance values are determined and the Nyquist criterion is applied to the model. Nyquist plots for stable and unstable conditions are displayed. Chapter V covers the application of a Lyapunov-based large-signal stability method to a simplified system model to ensure that large system disturbances are evaluated in addition to the earlier small-signal models. Specifically, the equilibrium point criterion and mixed potential criterion are evaluated. Finally, Chapter VI presents the conclusions and discusses areas available for further research.

II. SYNCHRONOUS MACHINE – RECTIFIER MODELING

A. REDUCED-ORDER MACHINE DEVELOPMENT

The first step in developing an overall model is accurately modeling the electrical source, which in the system being evaluated is a three-phase, ac synchronous generator connected to a phase-controlled rectifier. A detailed, valve-by-valve simulation is computationally intensive and results in considerably long run times. Since the dynamic effects of the system are important for the analysis, a time-efficient reduced-order model is used for simulation and analytical purposes. Figure II-1 shows a synchronous machine depicted as a voltage-in / current-out model. The machine terminal voltages, therefore, are required as both inputs to the generator governing equations and for use in determining the commutation properties of the thyristors in the rectifier. Thus, there is an inherent algebraic incompatibility that must be resolved by the model synthesis.

1. Approach

The following methodical approach was used in the development of the reduced-order model. The machine stator electrical transients (known as the "fast" transients) were ignored for simulation purposes. A voltage-behind-reactance (VBR) representation of the synchronous machine was then derived. The VBR model was subsequently used along with the different system modes to evolve an equation for the average direct current output voltage of the rectifier (V_{dc}). The source representation was completed by establishing the required synchronous machine stator currents.

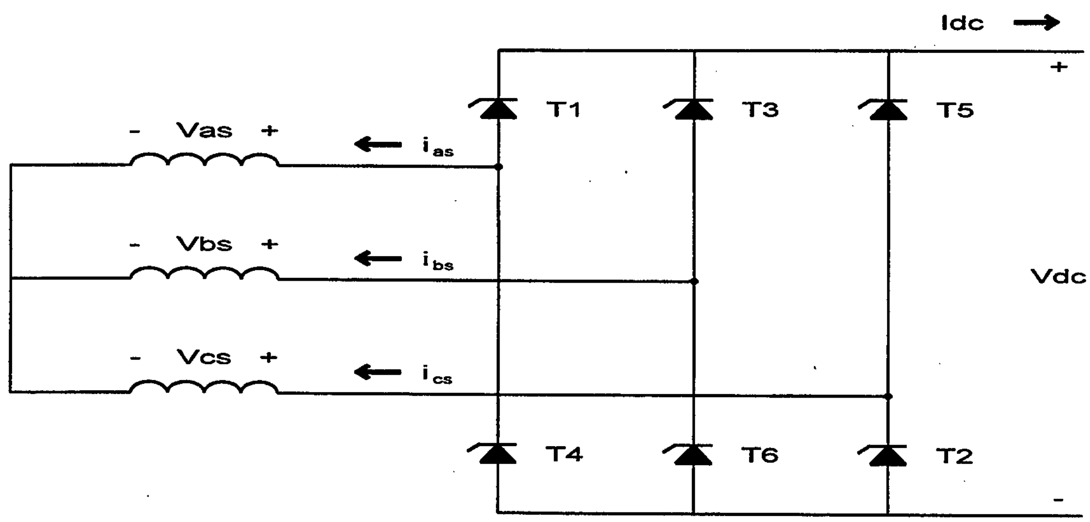

Figure II-1 Synchronous Machine / Rectifier Model

2. Synchronous Machine Modeling Equations

From reference [16], the equations used to describe a reduced-order synchronous machine are given. These equations were derived by setting the derivatives of the stator flux linkages per second equal to zero and fixing the reference frame speed equal to ω_e (the electrical angular velocity). Further, assuming an isolated synchronous machine in this case, we find that $\omega_e = \omega_r$ (the rotor electrical angular velocity). The stator voltage equations are as follows:

$$v_{qs}^r = r_s\, i_{qs}^r + \frac{\omega_r}{\omega_b} \Psi_{ds}^r \qquad (1)$$

$$v_{ds}^r = r_s\, i_{ds}^r + \frac{\omega_r}{\omega_b} \Psi_{qs}^r \qquad (2)$$

where v_{qs}^r and v_{ds}^r are the machine terminal voltages expressed in the rotor reference frame (RRF), i_{qs}^r and i_{ds}^r are the stator currents in the RRF, Ψ_{qs}^r and Ψ_{ds}^r are the stator flux linkages per second in the RRF, and ω_b is the base electrical angular velocity of the machine. The transformation matrix which relates the RRF quantities to the abc reference frame quantities is:

$$f^r_{qd0s} = \begin{bmatrix} \frac{2}{3}\cos\theta_r & \frac{2}{3}\cos\left(\theta_r - \frac{2\pi}{3}\right) & \frac{2}{3}\cos\left(\theta_r + \frac{2\pi}{3}\right) \\ \frac{2}{3}\sin\theta_r & \frac{2}{3}\sin\left(\theta_r - \frac{2\pi}{3}\right) & \frac{2}{3}\sin\left(\theta_r + \frac{2\pi}{3}\right) \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{bmatrix} f_{abcs} \tag{3}$$

where f^r_{qd0s} is a vector of transformed quantities, for instance f^r_{qs}, f^r_{ds}, and f_{os}. The vector f_{abcs} is a vector of machine quantities, for instance f_{as}, f_{bs}, and f_{cs}. The 'f' may represent voltage (v), current (i), or flux linkage per second (Ψ).

Rotor-referred voltage equations are written as:

$$0 = r'_{kq}\, i'_{kq} + \frac{1}{\omega_b}\frac{d}{dt}\Psi'_{kq} \tag{4}$$

$$0 = r'_{kd}\, i'_{kd} + \frac{1}{\omega_b}\frac{d}{dt}\Psi'_{kd} \tag{5}$$

$$v'_{fd} = r'_{fd}\, i'_{fd} + \frac{1}{\omega_b}\frac{d}{dt}\Psi'_{fd} \tag{6}$$

where r'_{kq}, r'_{kd}, and r'_{fd} are the referred winding resistances of the rotor coils. The referred values, designated by the primed quantities, are simply scaled versions of actual machine quantities. The scaling factor is related to the ratio of winding turns between the rotor and the stator (see [22].).

Stator flux linkage per second equations are given by:

$$\Psi^r_{qs} = X_{ls}\, i^r_{qs} + X_{mq}\left(i^r_{qs} + i'_{kq}\right) \tag{7}$$

$$\Psi^r_{ds} = X_{ls}\, i^r_{ds} + X_{md}\left(i^r_{ds} + i'_{kd} + i'_{fd}\right) \tag{8}$$

Rotor-referred flux linkage per second equations are expressed by:

$$\Psi'_{kq} = X'_{lkq}\, i'_{kq} + X_{mq}\left(i^r_{qs} + i'_{kq}\right) \tag{9}$$

$$\Psi'_{kd} = X'_{lkd}\, i'_{kd} + X_{md}\left(i^r_{ds} + i'_{kd} + i'_{fd}\right) \tag{10}$$

$$\Psi'_{fd} = X'_{lfd}\, i'_{fd} + X_{md}\left(i^r_{ds} + i'_{kd} + i'_{fd}\right) \tag{11}$$

where the various reactances are constants for a given machine provided operation remains magnetically linear.

One expression for the torque may be written in terms of the stator currents and stator flux linkages per second:

$$T_e = \frac{3P}{4\omega_b}\left(\Psi^r_{ds} i^r_{qs} - \Psi^r_{qs} i^r_{ds}\right) \tag{12}$$

where P is the number of poles of the machine.

The state variables for the system are Ψ'_{kq}, Ψ'_{kd}, Ψ'_{fd}, ω_r, and θ_r. The stator flux linkages per second are not state variables since we have ignored the derivative terms in those voltage equations. The next step is to express Ψ^r_{qs} and Ψ^r_{ds} in terms of state variables and stator current. Solving (10) and (11) for i'_{kd} and i'_{fd} and solving (9) for i'_{kq}, we find:

$$\begin{bmatrix} i'_{kd} \\ i'_{fd} \end{bmatrix} = \frac{\begin{bmatrix} X'_{fd} & -X_{md} \\ -X_{md} & X'_{kd} \end{bmatrix}}{X'_{kd}X'_{fd} - X^2_{md}} \begin{bmatrix} \Psi'_{kd} - X_{md} i^r_{ds} \\ \Psi'_{fd} - X_{md} i^r_{ds} \end{bmatrix} \tag{13}$$

$$i'_{kq} = \frac{\Psi'_{kq}}{X'_{kq}} - \frac{X_{mq}}{X'_{kq}} i^r_{qs} \tag{14}$$

Equations (13) and (14) are substituted into the stator flux linkage per second Equations (7) and (8) to yield:

$$\Psi^r_{qs} = X''_q i^r_{qs} + \Psi''_q \tag{15}$$

$$\Psi^r_{ds} = X''_d i^r_{ds} + \Psi''_d \tag{16}$$

where the q and d-axis subtransient reactances are denoted X''_q and X''_d, and the q and d-axis subtransient flux linkages per second are denoted Ψ''_q and Ψ''_d. It can be noted that the subtransient flux linkages per second are functions of the state variables of the synchronous machine. The next step is to then substitute Equations (15) and (16) into the stator voltage Equations (1) and (2) to give:

$$v_{qs}^r = r_s i_{qs}^r + \frac{\omega_r}{\omega_b} X_d^" i_{ds}^r + \frac{\omega_r}{\omega_b} \Psi_d^" \tag{17}$$

$$v_{ds}^r = r_s i_{ds}^r - \frac{\omega_r}{\omega_b} X_q^" i_{qs}^r - \frac{\omega_r}{\omega_b} \Psi_q^" \tag{18}$$

It is customary to define:

$$E_q^" = \frac{\omega_r}{\omega_b} \Psi_d^" \tag{19}$$

$$E_d^" = -\frac{\omega_r}{\omega_b} \Psi_q^" \tag{20}$$

then Equations (17) and (18) can be rewritten:

$$v_{qs}^r = r_s i_{qs}^r + \frac{\omega_r}{\omega_b} X_d^" i_{ds}^r + E_q^" \tag{21}$$

$$v_{ds}^r = r_s i_{ds}^r - \frac{\omega_r}{\omega_b} X_q^" i_{qs}^r + E_d^" \tag{22}$$

Equations (21) and (22) are the desired reduced-order voltage-behind-reactance (VBR) representation of the synchronous machine.

3. Modeling Average DC Voltage

The next step involved in modeling the electrical power source is to derive an expression for the average dc voltage using the VBR model together with boundary values associated with the conduction of the rectifier. In reference[16], the technique used was to find the average dc voltage during a single switching interval, since each of the six steady-state switching intervals in a three-phase rectifier are identical. During a single switching interval, the average dc voltage is a function of the phase voltages of two of the phases of the synchronous machine over the switching interval as shown by:

$$V_{dc} = \frac{1}{\pi/3} \int_{\theta_r = \frac{\pi}{3}+\beta}^{\theta_r = \frac{2\pi}{3}+\beta} (v_{bs} - v_{cs}) d\theta_r \tag{23}$$

where β is the firing delay angle from the natural point of commutation with respect to the rotor position [16].

The VBR model can be used to show that:

$$V_{dc} = \frac{3}{\pi}\frac{\omega_r}{\omega_b}(\Psi_{bs} - \Psi_{cs})\Big|_{\theta_r=\frac{\pi}{3}+\beta}^{\theta_r=\frac{2\pi}{3}+\beta} \tag{24}$$

The small effect of the stator resistance is ignored.

The flux linkages per second can then be determined at the two limits using the DC currents at each limit to yield the following equation for the average dc voltage:

$$V_{dc} = \frac{3\sqrt{3}}{\pi}\frac{\omega_r}{\omega_b}\sqrt{(\Psi_q^{"})^2 + (\Psi_d^{"})^2}\cos\alpha - \frac{3}{\pi}\frac{\omega_r}{\omega_b}\left[\left(\frac{X_q^{"} + X_d^{"}}{2}\right)I_{dc} + \left(X_d^{"} - X_q^{"}\right)I_{dc}\sin\left(2\beta + \frac{\pi}{6}\right)\right] \tag{25}$$

where α is the firing delay angle from the natural point of commutation with respect to the source electrical angle [16].

4. Calculation of Stator Currents

The final step in modeling the power source is to calculate the stator currents. This is necessary since the referred rotor currents (Equations (13) and (14)) are expressed in terms of rotor-referred flux linkages per second and rotor reference frame stator currents. In the developed model, the rotor reference frame stator currents are needed to update the state of the machine during each time step iteration. The non-ideal case of the current flow through the six individual thyristors as a function of the three-phase synchronous generator output as shown in Figure II-2. As it would be expected, these

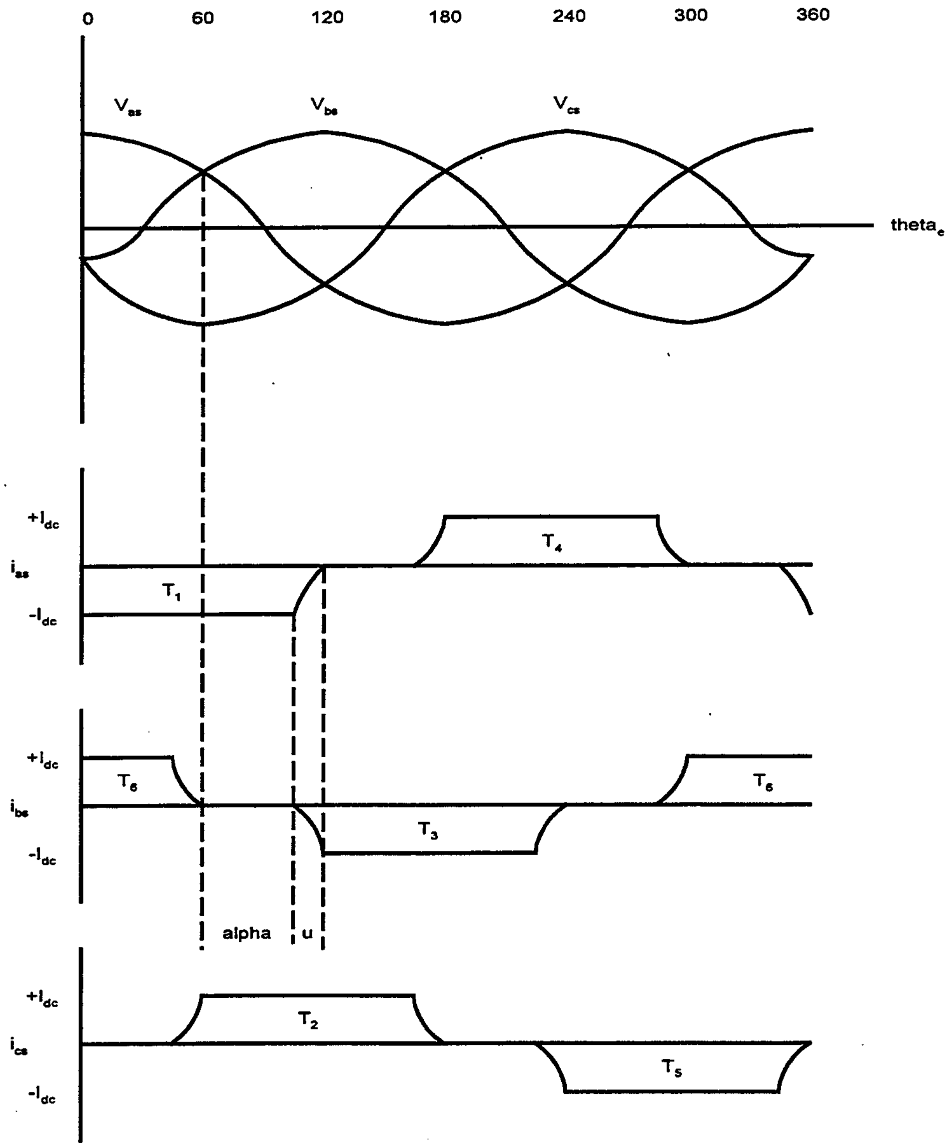

Figure II-2 Non-Ideal Thyristor Currents

currents, like V_{dc}, are also periodic with a fundamental frequency of $6\omega_r$. The average q and d- currents can be determined over the same interval as that used for V_{dc}:

$$i^r_{qs,ave} = \frac{1}{\pi/3} \int_{\frac{\pi}{3}+\beta}^{\frac{2\pi}{3}+\beta} i^r_{qs}(\theta_r)d\theta_r \tag{26}$$

$$i^r_{ds,ave} = \frac{1}{\pi/3} \int_{\frac{\pi}{3}+\beta}^{\frac{2\pi}{3}+\beta} i^r_{ds}(\theta_r)d\theta_r \tag{27}$$

The non-ideal switching interval can further be divided into two distinct events. The first part of the switching interval, called the conduction period, consists of the section of time that there is only one device conducting current on each rail. The second part of the switching interval, called the commutation period, occurs when current is being transferred from one device to another device on the same rail. Thus:

$$i^r_{qs,ave} = i^r_{qs,com} + i^r_{qs,cond} \tag{28}$$

$$i^r_{ds,ave} = i^r_{ds,com} + i^r_{ds,cond} \tag{29}$$

If u is defined as the conduction angle, then Equations (26) and (27) can be subdivided into the conduction and commutation periods as follows:

$$i^r_{qs,com} = \frac{1}{\pi/3} \int_{\frac{\pi}{3}+\beta}^{\frac{\pi}{3}+\beta+u} i^r_{qs}(\theta_r)d\theta_r \tag{30}$$

$$i^r_{ds,com} = \frac{1}{\pi/3} \int_{\frac{\pi}{3}+\beta}^{\frac{\pi}{3}+\beta+u} i^r_{ds}(\theta_r)d\theta_r \tag{31}$$

$$i^r_{qs,cond} = \frac{1}{\pi/3} \int_{\frac{\pi}{3}+\beta+u}^{\frac{2\pi}{3}+\beta} i^r_{qs}(\theta_r)d\theta_r \tag{32}$$

$$i^r_{ds,cond} = \frac{1}{\pi/3} \int_{\frac{\pi}{3}+\beta+u}^{\frac{2\pi}{3}+\beta} i^r_{ds}(\theta_r)d\theta_r \tag{33}$$

Since the currents are known at the boundaries of the conduction interval, modeling equations for the conduction currents are easily obtained from Equations (32) and (33):

$$i_{qs,cond}^{r} = \frac{2\sqrt{3}}{\pi} I_{dc} \left[\cos\left(\beta + \frac{2\pi}{3}\right) - \cos\left(\beta + u + \frac{\pi}{3}\right) \right] \tag{34}$$

$$i_{ds,cond}^{r} = \frac{2\sqrt{3}}{\pi} I_{dc} \left[\sin\left(\beta + \frac{2\pi}{3}\right) - \sin\left(\beta + u + \frac{\pi}{3}\right) \right] \tag{35}$$

The only unknown in the above equations is the commutation angle (u). This can be found while examining the commutation period dynamics. Finding the commutation currents is a more difficult endeavor. During commutation, two of the phases are shorted together. As a result, the difference between the flux linkages per second of the two phases is a constant, specified in [16] as K_1. The quantity i_{as} can be solved for in the abc reference frame yielding:

$$i_{as} = \frac{K_1 - \sqrt{3}\left[\Psi_q'' \cos\left(\theta_r + \frac{\pi}{6}\right) + \Psi_d'' \sin\left(\theta_r + \frac{\pi}{6}\right) \right]}{\left(X_q'' - X_d''\right)\cos\left(2\theta_r + \frac{\pi}{3}\right) + \left(X_q'' + X_d''\right)} - \frac{\left[\left(X_q'' - X_d''\right)\cos\left(2\theta_r + \frac{2\pi}{3}\right) + \frac{1}{2}\left(X_q'' + X_d''\right) \right] I_{dc}}{\left(X_q'' - X_d''\right)\cos\left(2\theta_r + \frac{\pi}{3}\right) + \left(X_q'' + X_d''\right)} \tag{36}$$

where the aforementioned K_1 is:

$$K_1 = \sqrt{3}\left(-\Psi_q'' \cos\beta + \Psi_d'' \sin\beta\right)\left[\left(X_d'' - X_d''\right)\cos\left(2\beta + \frac{2\pi}{3}\right) - \frac{1}{2}\left(X_q'' + X_d''\right) \right] I_{dc} \tag{37}$$

When commutation is complete, i_{as} as a function of θ_r is zero. An implicit expression for the commutation angle u is found by setting i_{as} equal to zero in Equation (36):

$$\begin{aligned} f_{com1}(u) &= K_1 - \sqrt{3}\left[-\Psi_q'' \sin(\beta + u) + \Psi_d'' \cos(\beta + u) \right] \\ &- \left[\left(X_q'' - X_d''\right)\cos\left(2\beta + 2u - \frac{2\pi}{3}\right) + \frac{1}{2}\left(X_q'' + X_d''\right) \right] I_{dc} \end{aligned} \tag{38}$$

Given the state of the machine, the dc link and the firing angle, the commutation angle can be determined by setting Equation (38) equal to zero and solving for u. This is done in the simulation by iteration to achieve a commutation angle within 0.001 radians. The iterative method used simply involves halving the range in which the commutation angle exists during each step until the range is narrowed to the above stated tolerance. Once u is calculated, the conduction current components can be determined using Equations (34) and (35).

The q and d-stator currents in the RRF are defined during the commutation period as:

$$i_{qs}^{r} = \frac{2\sqrt{3}}{3}\left[i_{as}\cos\left(\theta_r + \frac{\pi}{6}\right) - I_{dc}\sin\theta_r\right] \tag{39}$$

$$i_{ds}^{r} = \frac{2\sqrt{3}}{3}\left[i_{as}\sin\left(\theta_r + \frac{\pi}{6}\right) + I_{dc}\cos\theta_r\right] \tag{40}$$

Equation (36) is substituted into the above equations, which are then substituted into Equations (30) and (31). The resulting integrals cannot be solved by analytical methods. Instead, a numerical method of integration called the Simpson method is used [16]. The Simpson method yields the following equations for the commutation currents over the commutation angle by utilizing a weighted measurement of the q and d-currents at increments through the commutation process, including the boundaries:

$$i_{qs,com}^{r} = \frac{3}{\pi}\frac{u}{12}\left[i_{qs}^{r}\Big|_{\theta_r=\beta+\frac{\pi}{3}} + 4i_{qs}^{r}\Big|_{\theta_r=\beta+\frac{\pi}{3}+\frac{u}{4}} + 2i_{qs}^{r}\Big|_{\theta_r=\beta+\frac{\pi}{3}+\frac{u}{2}} + 4i_{qs}^{r}\Big|_{\theta_r=\beta+\frac{\pi}{3}+\frac{3u}{2}} + i_{qs}^{r}\Big|_{\theta_r=\beta+\frac{\pi}{3}+u}\right] \tag{41}$$

$$i_{ds,com}^{r} = \frac{3}{\pi}\frac{u}{12}\left[i_{ds}^{r}\Big|_{\theta_r=\beta+\frac{\pi}{3}} + 4i_{ds}^{r}\Big|_{\theta_r=\beta+\frac{\pi}{3}+\frac{u}{4}} + 2i_{ds}^{r}\Big|_{\theta_r=\beta+\frac{\pi}{3}+\frac{u}{2}} + 4i_{ds}^{r}\Big|_{\theta_r=\beta+\frac{\pi}{3}+\frac{3u}{2}} + i_{ds}^{r}\Big|_{\theta_r=\beta+\frac{\pi}{3}+u}\right] \tag{42}$$

Now that both the conduction and commutation currents are known, the average RRF stator currents are calculated with Equations (28) and (29). These currents are then

injected into the synchronous machine rotor flux linkage per second equations shown in Equations (15) and (16).

B. DESCRIPTION OF ACSL CODE AND SIMULATION

The derived model is programmed in the Advanced Continuous Simulation Language (ACSL) . A listing of the .csl and .cmd files is documented in Appendix A. The .csl file contains the equation description of the synchronous generator-phase controlled rectifier in ACSL statement format. The .cmd file contains sets of runtime instructions to manipulate the model output into a usable form. ACSL was chosen for its execution speed and its strength and ease of working with and sorting continuous modeling equations. The feature is desirable due to the number of variables involved with the model as well as the interconnectivity of the numerous variables.

1. .CSL File Description

A block diagram representation of the model in terms of the required inputs and resultant outputs is shown in Figure II-3. The initial section of the .csl file holds the machine constants used in the test model. The assumed per unit electrical machine parameters were taken from reference [17] for the following: r_s, X_{ls}, X_{mq}, X_{md}, I_{dc}, X'_{lkd}, X'_{lfd}, X'_{lkq}, r'_{kd}, r'_{fd}, r'_{kq} and e_{xfd}, where the leakage reactance terms with a subscript "l" are used to calculate the q and d-axis subtransient reactances (X''_q and X''_d).

The derivative section contains the equations that describe the system. Within the derivative section, there are two subroutine calls and two function calls. The two FORTRAN subroutines implement the Simpson method described in reference [16] to calculate the five different current components in equations (40) and (41). The first FORTRAN function calculates the commutation angle (u) as described in an earlier

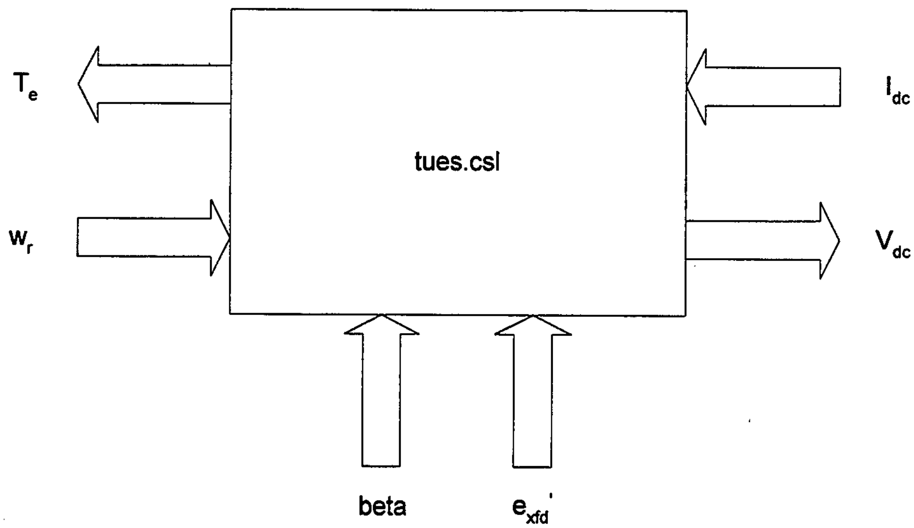

Figure II-3 Block Diagram of Synchronous Generator-Phase Controlled Rectifier ACSL Model

section. The second FORTRAN function calculates the firing delay angle with respect to rotor angle (β) using the same method as adopted for calculating u.

The model accounts for the fact that β must be set such that the thyristor is not gated until after it is forward biased by constraining β to a minimum value, $\beta_{\min}$, that denotes the earliest that a thyristor can be turned on. The firing angle for the thyristor with respect to the point its anode-to-cathode voltage becomes positive is then represented by $\hat{\alpha}$, which is the difference between β and $\beta_{\min}$.

2. .CMD File Description

The .cmd file is configured to run a simulation to produce data points which define V_{dc} and T_e as a function of β. The resulting graphs for $I_{dc} = 0.9$ pu are shown in Figure II-4. The effect of this is constant values for V_{dc} and T_e at values of β less than the minimum value that represents gating the thyristor prior to it being forward biased. It can be seen from the graphs that $\beta_{\min}$ is at approximately 30°. With β equal to $\beta_{\min}$, V_{dc} and T_e are at their extreme per unit values of 1.4 and –0.85 respectively. V_{dc} and T_e

change linearly as β is increased in value when it is greater than $\beta_{\min}$. V_{dc} decreases from a positive value and T_e increasing from a negative value, corresponding to generator action. When β exceeds approximately 70°, the average dc voltage becomes negative and the average torque becomes positive, corresponding to motor action. This linear region lasts until β reaches approximately 105°.

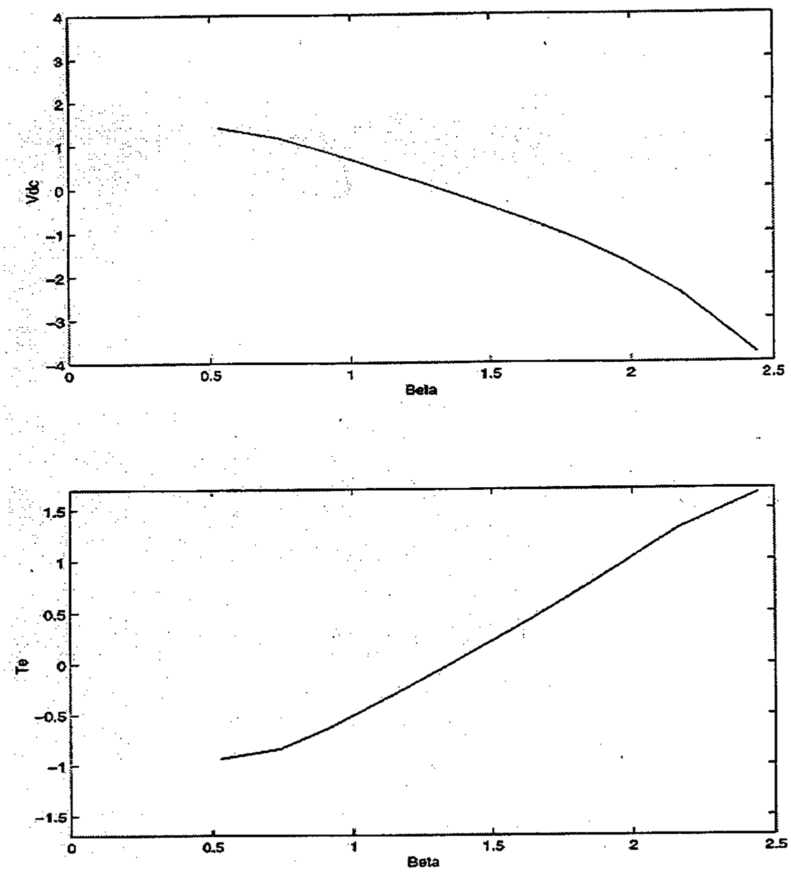

Figure II-4 Beta vs Vdc and Te

A detailed description of a model for the system source has now been presented. The next chapter discusses the evaluation of a simplified dc link-converter model for stability criteria in terms of major system parameters.

III. SIMPLIFIED DC LINK/CONVERTER MODEL

A. DEVELOPMENT OF THE MODEL

One characteristic predominant in dc-dc converters is the apparent small-signal negative input impedance which is a result of the high bandwidth regulation that makes the converter appear as a constant power sink. In Ref. [18], it is noted that one method that can be used to ensure stability is to increase the dc link capacitance. This is not a desirable remedy since it requires the use of more space and increases the weight contribution of the overall distribution system. In addition, since electrolytic capacitors have relatively low reliability, large banks are unattractive owing to the time-intensive task of identifying a shorted capacitor. The authors in [18] develop a simplified model, as shown in Figure III-1, to illustrate the cause of negative input impedance instability.

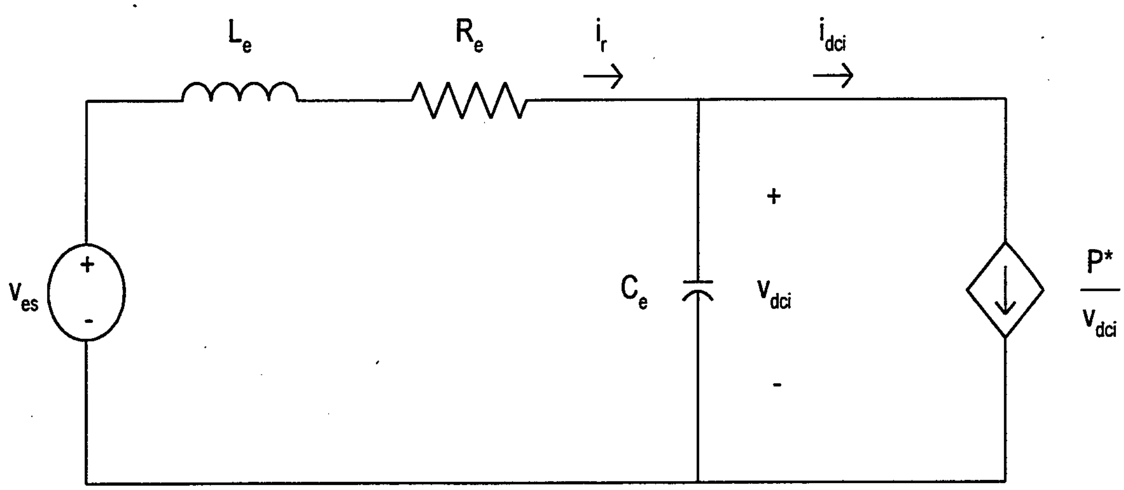

Figure III-1 Simplified DC Link Model

Several simplifying assumptions are made. First, the prime mover and voltage regulator dynamics are assumed to have significantly long time constants. Second, all losses in the machine and rectifier are assumed to be zero. Third, the rectifier is assumed

to be uncontrolled and finally, field voltage regulation maintains the source voltage equal to the commanded source voltage resulting in no need for subtransient information.

The equations which describe the non-linear simplified model are then found to be:

$$\frac{d\,i_r}{dt} = -\frac{1}{L_e} v_{dci} - \frac{R_e}{L_e} i_r + \frac{1}{L_e} v_{es} \tag{43}$$

$$\frac{d\,v_{dci}}{dt} = \frac{1}{C_e} i_r - \frac{P^*}{C_e v_{dci}} \tag{44}$$

where L_e is a function of the filter inductance and the transient commutating inductance; R_e is a function of the commutating inductance, machine stator resistance, and link filter resistance; and C_e includes the filter capacitance and any input capacitance associated with the converter. P^* is the assumed constant power being drawn by the converter. Linearization of the above equations result in:

$$\frac{d\,\Delta i_r}{dt} = -\frac{1}{L_e} \Delta v_{dci} - \frac{R_e}{L_e} \Delta i_r + \frac{1}{L_e} \Delta v_{es} \tag{45}$$

$$\frac{d\,\Delta v_{dci}}{dt} = \frac{1}{C_e} \Delta i_r - \frac{P^*}{C_e v_{dci}^2} \Delta v_{dci} \tag{46}$$

Furthermore, the linearized converter input current is:

$$\Delta i_{dci} = \frac{\partial}{\partial v_{dci}} \left[\frac{P^*}{v_{dci}} \right] \Delta v_{dci} = \frac{-P^*}{v_{dci}^2} \Delta v_{dci} \tag{47}$$

Thus, the small-signal converter input impedance may be found from:

$$Z_{conv} = \frac{\Delta v_{dci}}{\Delta i_{dci}} = -\frac{v_{dci}^2}{P^*} \tag{48}$$

Therefore, for a given power being supplied by the converter and a given input voltage v_{dci}, the input impedance must be negative. It is this negative resistance which sets up the possibility for oscillations with the input LC filter.

B. EVALUATION OF THE MODEL

Confirmation that the negative input impedance results in system instability is obtained by examining the characteristic equation of the model. In order for the system to be stable, a necessary and sufficient condition of the Hurwitz criterion requires that all coefficients of a second-order characteristic equation be positive. From Equations (45) and (46), the characteristic equation for the system is:

$$\lambda^2 + \left(\frac{R_e}{L_e} - \frac{P^*}{C_e v_{dci}^2}\right)\lambda + \left(\frac{1}{L_e C_e} - \frac{P^* R_e}{C_e L_e v_{dci}^2}\right) = 0 \tag{49}$$

The resulting stability requirements are then:

$$\frac{R_e}{L_e} > \frac{P^*}{C_e v_{dci}^2} \tag{50}$$

and:

$$\frac{v_{dci}^2}{P^*} > R_e \tag{51}$$

Equation (51) is typically satisfied by matching the load characteristics to the given source resistance. Thus, Equation (50) becomes a first-order design criterion for the link filter parameters. A rearranged version of Equation (50) illustrates that we can ensure small-signal stability by including additional bus capacitance such that:

$$\frac{C_e}{L_e} > \frac{P^*}{R_e v_{dci}^2} \tag{52}$$

ACSL code for the .CSL and .CMD files which model both the linearized and non-linearized representations of the model is given in Appendix C. Simulations were conducted in which P^* was assumed to be 200 kW, v_{dci} was assumed to be 1100V, R_e was assumed to be 0.01 Ω, and L_e was assumed to be 0.5 mH. This resulted in requiring C_e to be 8265 μF to just be stable in the event of large disturbances.

The simulated output of a transient from 10% rated power to 100% rated power at time 0.5 seconds and a return to 10% rated power at time 3 seconds is shown in Figure

III-2. A value of $C_e = 8500\ \mu F$ was used to better show the stable response due to the low damping of this configuration. The system can be seen to be stable after both the up-power and down-power transients. The simulated output of a similar transient sequence with the down-power transient occuring at time 0.6 seconds is shown in Figure III-3. For this simulation, C_e was lowered to $826.5\ \mu F$. It is shown that following the up-power transient, the system becomes unstable. Stability is not recovered following the down-power transient.

We have now established the governing stability criteria dictated by a simplified dc link/converter model. In the next chapter, we examine a more detailed model that defines the requirements for stability using subsystem impedances.

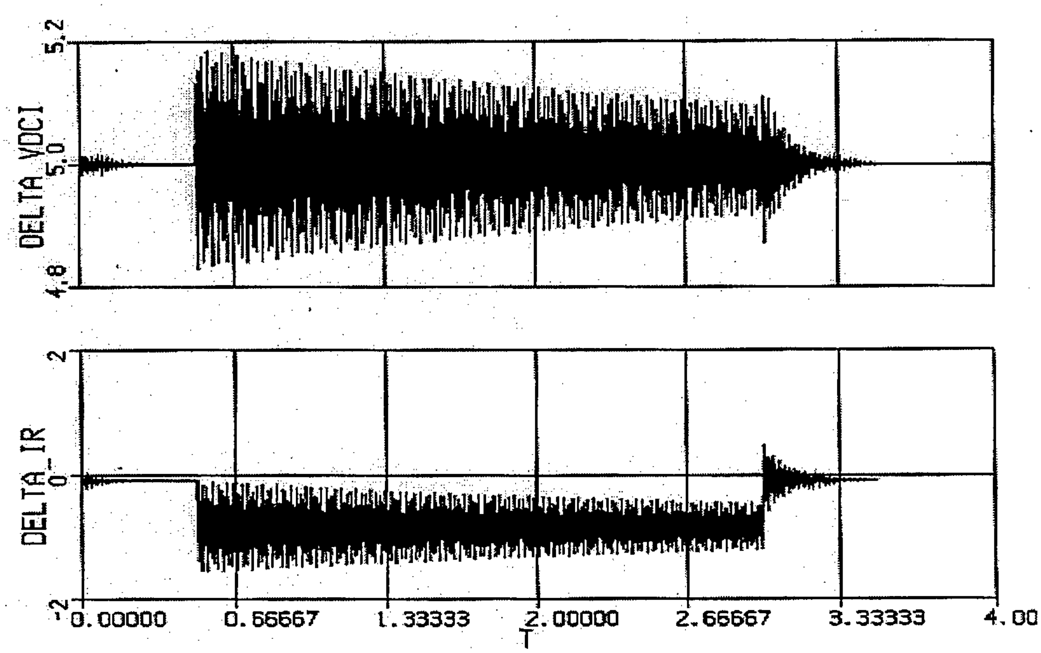

Figure III-2 Up-Power, Down-Power Transient, C_e = 8500 MicroFarads

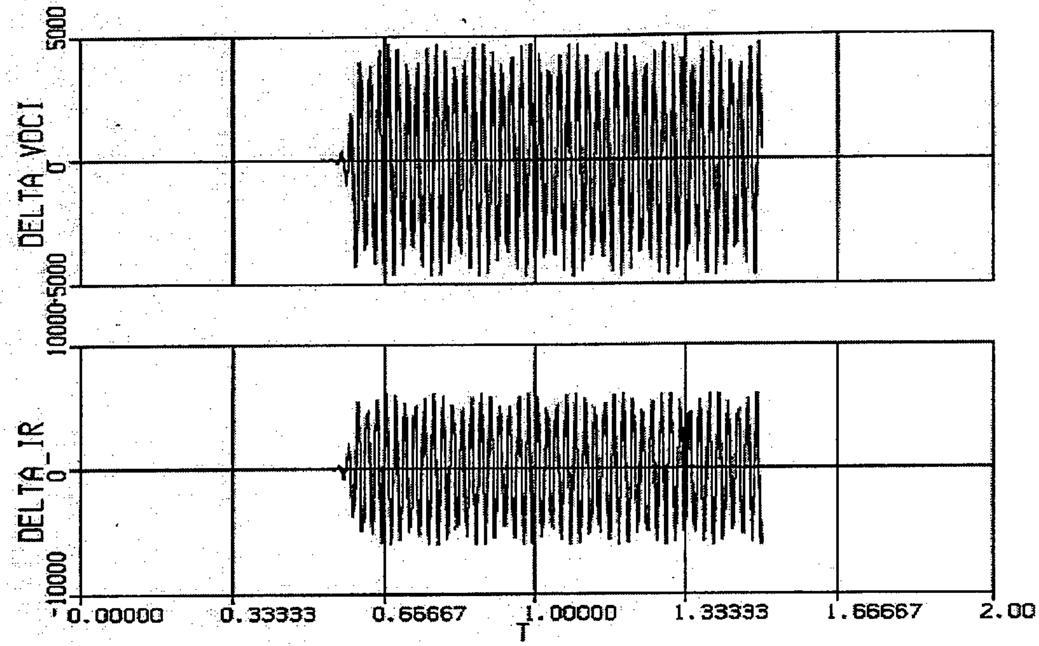

Figure III-3 Up-Power, Down-Power Transient, C_e = 826.5 MicroFarads

IV. IMPEDANCE-BASED STABILITY CONSTRAINTS

A. STABILITY CRITERIA USING SUBSYSTEM IMPEDANCES

One analysis that can be conducted to determine the stability of the overall system involves determining the input impedance of the dc converter and the output impedance of the filter. Together, the poles of the overall system transfer function are found. The transfer function can then be examined to determine if the Nyquist stability criteria are met. The steps involved in this process are: design the converter to be used, determine the converter controller gains, calculate the converter input impedance, calculate the filter output impedance, and use the results to analyze stability. For analysis purpose, two converters are developed for use in simulations. The first is designed for a low switching frequency used for a high-power hard switching process. The second will be designed for a higher switching frequency used for a high-power soft switching process.

B. DESIGN OF THE DC CONVERTER

The layout of a common step-down dc-dc converter in a Buck Chopper configuration is shown in Figure IV-1. To design the converter, the first issue which must be resolved is the system requirements. To establish a baseline for the design, we require maintaining continuous current conduction mode for all loads that are greater than ten percent of the rated power. For this thesis, the design specifications listed in Table IV-1 are assumed.

Specification	Value
Rated Power (P_{rat})	200 kW
Filter Output Voltage (V_{dc})	1100 V
Load Voltage (V_{out})	950 V
Ripple Voltage (ΔV_{out})	5 V
Hard Switching Frequency ($f_{s,hard}$)	4 kHz
Soft Switching Frequency ($f_{s,soft}$)	20 kHz

Table IV-1 Design Specifications for the DC-DC Converter

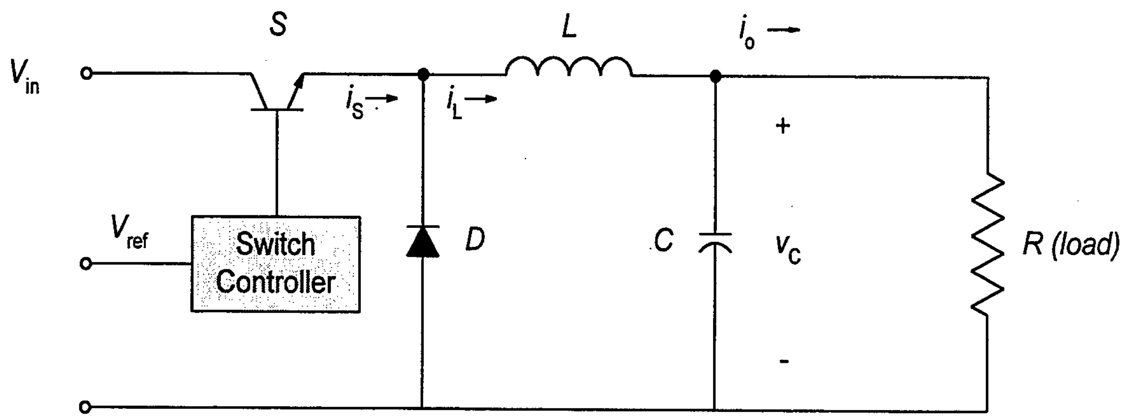

Figure IV-1 DC-DC Converter - Buck Chopper

1. Design of the Components

The authors in [19] outline a sound methodology for converter design. The nominal duty cycle (D_o) of the switch is defined as the percentage of time that the switch is closed. For the designed converter, assuming continuous current conduction, we get:

$$D_o = \frac{V_{out}}{V_{dc}} = \frac{950V}{1100V} = 0.8636 \qquad (53)$$

Next, based on the rated power and the desired output voltage, the rated load resistance can be found by:

$$R_{rat} = \frac{V_{out}^2}{P_{rat}} = \frac{(950V)^2}{200kW} = 4.5125\Omega \tag{54}$$

The critical resistance (R_{crit}) is the load resistance at the boundary between continuous and discontinuous current conduction modes. For this converter:

$$R_{crit} = 10 \times R_{rat} = (10) \times (4.5125\Omega) = 45.125\Omega \tag{55}$$

The main components of the converter can now be selected. The hard switching converter parameters are determined first. The critical inductance (L_{crit}) is the minimum inductance required to maintain continuous current conduction mode during all conditions required by the design specifications. The critical inductance is found by:

$$L_{crit} = \frac{R_{crit}}{2f_s}(1 - D_o) = 769.4\mu H \tag{56}$$

In order to maintain a comfortable margin, L is assumed to be 1mH.

The minimum capacitance is designed around ensuring that the steady-state output voltage ripple specification is met:

$$C_{\min} = \frac{D_o}{8L_{crit} f_{s,hard}^2 \Delta V_{out}}(V_{dc} - v_{out}) = 202.4\mu F \tag{57}$$

Once again, a margin is included to ensure that the capacitor is large enough to provide sufficient energy during a transient to maintain output voltage. The capacitor selected should not be too large, however, because this would result in small changes in output voltage causing the duty cycle to oscillate between full-on and full-off. C is assumed to be 2mF.

2. Converter Controller Design

The buck chopper exhibits an oscillatory response as a result of the undamped L-C filter at the converter output. To ensure that the converter operates satisfactorily

during transients and to provide steady-state converter regulation, a multi-loop feedforward controller is utilized for duty cycle control. The governing controller equation is [19]:

$$d(t) = \frac{V_{ref}}{V_{dc}} + h_v K_v \left(V_{ref} - v_{out}\right) + h_n K_v \int \left(V_{ref} - v_{out}\right) dt + h_i K_i \left(i_L - i_{out}\right) \tag{58}$$

where h_v, h_n, and h_i are the feedback gains, K_v and K_i are the voltage and current sensor gains, V_{ref} is the desired output voltage, and i_{out} is the sensed output current. This controller design assumes that the converter is operating autonomously. Additional terms are required to parallel multiple dc-dc converters. The first component of Equation (58) provides feedforward action to ensure rapid response to disturbances in the input voltage. The second and third terms implement a proportional-plus-integral (PI) outer voltage control while the fourth term realizes an inner current control. Effectively, this last component represents the feedback of the derivative of the capacitor voltage so that a PID-type contol is realized.

By assuming that the desired output voltage (V_{ref}) remains constant and the converter load is purely resistive in nature, we find that the operation of the converter can be described by a set of averaged linear ordinary differential equations with the following characteristic polynomial:

$$s^3 + d_2 s^2 + d_1 s + d_0 \tag{59}$$

where d_2, d_1, and d_0 (functions of the converter parameters and control gains) describe the system pole locations and, ultimately, the converter's transient response. Upon selecting desired characteristic polynomial coefficients, we establish gain relationships as follows:

$$h_v K_v = \frac{LC}{V_{dc}} \left(d_1 - \frac{1}{LC} \right) \tag{60}$$

$$h_n K_v = \frac{d_0 LC}{V_{dc}} \tag{61}$$

$$h_i K_i = \frac{-L}{V_{dc}}\left(d_2 - \frac{1}{RC}\right) \tag{62}$$

The utilization of a third-order Bessel function polynomial as a system prototype is known to result in a desirable system response. In addition, it minimizes the distance that the open-loop poles must be moved and hence minimizes the control effort. The specific poles for the prototype system are located at:

$$s_{1,2} = -0.7455\omega \pm j0.7112\omega \tag{63}$$

$$s_3 = -0.9420\omega \tag{64}$$

where ω is the desired closed-loop bandwidth. The radian frequency (ω) must meet three criteria to provide optimized results. The first criteria is that ω must be at least one decade below the switching frequency to prevent undesirable controller-switch interactions. The second criteria is that ω should be minimized to prevent additional noise from being introduced into the system through the controller's operation. The final criteria is that ω must be large enough to achieve the desired settling time following a transient. As a result of these criteria, ω was chosen for the hard switching converter to be 1500 $^{rad}/_{sec}$. The poles for the designed converter are then:

$$s_{1,2} = -1118.25 \pm j1066.8 \tag{65}$$

$$s_3 = -1413 \tag{66}$$

The system characteristic equation is then:

$$s^3 + 3639.5s^2 + 5526354.8s + 3351129059.4 \tag{67}$$

and the gain selections become:

$$h_v K_v = 0.00914 \tag{68}$$

$$h_n K_v = 6.093 \tag{69}$$

$$h_i K_i = -0.003299 \tag{70}$$

Similar calculations were made for a soft switching buck chopper with a switching frequency of 20 kHz. L_{crit} was 153.9 μH, with a value of 200 μH chosen to provide a margin. C_{min} was found to be 40.5 μF, with a value of 400 μF chosen to

ensure adequate energy storage capacity. The desired system poles utilizing the Bessel prototype with $\omega = 3000\ ^{rad}/_{sec}$ are:

$$s_{1,2} = -2236.5 \pm j2133.6 \tag{71}$$

$$s_3 = -2826 \tag{72}$$

The resultant gains are:

$$h_v K_v = 0.00070508 \tag{73}$$

$$h_n K_v = 1.9636 \tag{74}$$

$$h_i K_i = -0.001317 \tag{75}$$

3. Filter – Converter Model in ACSL

The .csl and .cmd files for an ACSL model of a dc link filter attached to the input of a dc-dc converter with feedback control are contained in Appendix D. The model specifically contains the component parameters derived for the hard switching converter. It assumes an ideal dc input voltage. The initial conditions for the simulation are that the filter capacitor is fully charged and the converter is secured. Converter operation is initiated by ramping up the reference voltage. Converter control is implemented with the method outlined in the previous section.

Several simulations were run with various filter parameters. The behavior of the system with changes in the filter capacitance were of particular interest. When filter parameters were within those specifed by the stability requirements, the output was stable as expected. However, of interest was the observation of a region of stability outside of the criteria bounds established in the stability analysis. The band was observed to exist when filter capacitor values between approximately 25 μF and 110 μF were used in the simulations. It is believed that this region of stability is a result of the feedback control for this particular set of parameters. In general, changes in the filter capacitance resulted in changes in the ripple voltage magnitude and frequency.

C. IMPEDANCE CALCULATIONS

A representation of a source-filter-converter-load is shown in Figure IV-2, as also shown in reference [20]. The overall transfer function of this system is shown to be:

$$\frac{v_L}{v_s} = \frac{h_f h_c}{1 + Z_s / Z_i} \tag{76}$$

where Z_s is the output impedance of a line LC filter and source, and Z_i is the input impedance of a loaded converter with closed-loop control. Stability of the system can be determined by analyzing the poles of this transfer function. This section will describe how Z_s and Z_i are determined for this system as well as analyze the behavior of the poles of the system.

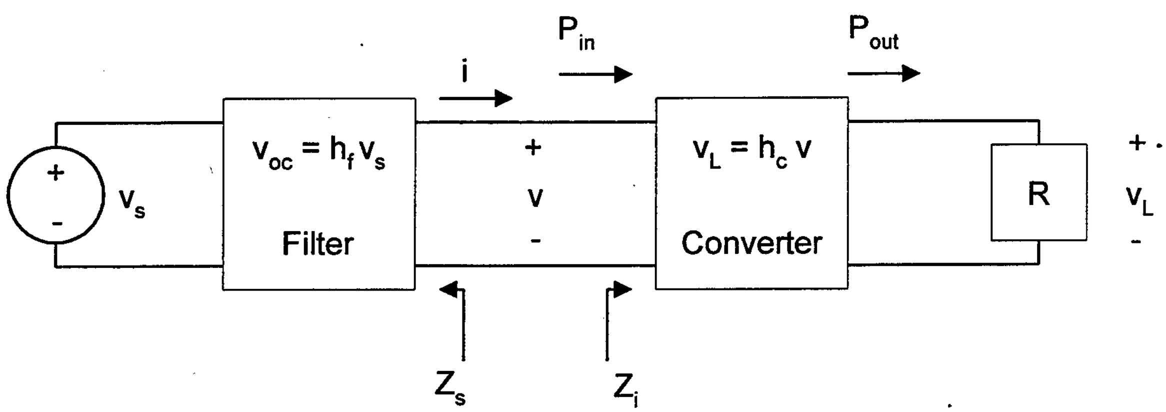

Figure IV-2 DC-DC Converter With Input Filter

1. Determination of Converter Input Impedance

Due to the non-linear nature of a buck chopper, determination of the input impedance needs to be performed on a linearized version of the model. Referring back to Figure IV-1, we find the input current is related to the averaged inductor current by:

$$i_b = d\, i_L \tag{77}$$

where d is the converter duty cycle. Linearization of Equation 67 yields:

$$\Delta i_b = d_o \Delta i_L + i_{Lo} \Delta d \tag{78}$$

where Δd is the perturbation variable given by :

$$\Delta d = d - d_o \tag{79}$$

The constants d_o and i_{Lo} are operating point values for those variables. By assuming ΔV_{ref} is zero, the linearization of Equation 48 can be shown to yield:

$$\Delta d = K_1 \Delta v_{in} + T_1(s) \Delta v_c \tag{80}$$

where K_1 is:

$$K_1 = \frac{-V_{ref,o}}{v_{in,o}^2} \tag{81}$$

and $T_1(s)$ is:

$$T_1(s) = \frac{h_i C s^2 + h_v s + h_n}{s} \tag{82}$$

Further definitions that are made involve the transfer function between the variation in input voltage (Δv_{in}) and the variation in the state variable inductor current (Δi_L) as well as the variation in the state variable capacitor voltage (Δv_c). These relationships are:

$$\Delta i_L = T_2(s) \Delta v_{in} \tag{83}$$

$$\Delta v_c = T_3(s) \Delta v_{in} \tag{84}$$

The MATLAB code used to determine the coefficients for $T_2(s)$ and $T_3(s)$ is contained in Appendix E. The method used to find these involves deriving the state-space form of the linearized system equations, then utilizing the state-space to transfer function (ss2tf) MATLAB function with a C matrix that zeros all outputs except Δi_L for the $T_2(s)$ calculation and Δv_c for the $T_3(s)$ calculation.

The desired input impedance is defined by:

$$Z_i = \frac{\Delta v_{in}}{\Delta i_b} \tag{85}$$

Equations (68), (70), (73), and (74) are then substituted into (75) to obtain:

$$Z_i(s) = \frac{1}{d_o T_2(s) + i_{L,o} K_1 + i_{L,o} T_1(s) T_3(s)} \tag{86}$$

The coefficients for the s terms are also determined by the MATLAB code in Appendix E. Input impedance calculations are performed for both the hard switching and soft switching converter options. Note, Equation (86) holds for the specific multi-loop control with feedforward under consideration.

2. Determination of Filter Output Impedance

Figure IV-3(a) is a representation of the simplified network looking back through the filter to the source. The network which is used to find the Thevenin equivalent impedance is shown in Figure IV-3(b). By appropriately combining series and parallel impedances:

$$Z_s(s) = \frac{\frac{1}{C_f} s + \frac{R_s}{C_f L_f}}{s^2 + \frac{R_s}{L_f} s + \frac{1}{C_f L_f}} \tag{87}$$

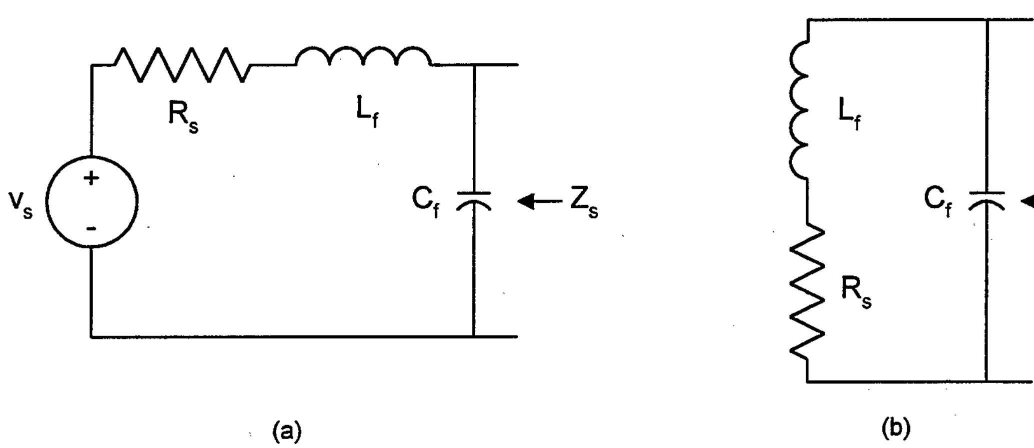

Figure IV-3 Filter Output Impedance (a) Simplified System Diagram, (b) Thevenin Equivalent Impedance Network

3. Impedance-Based Stability Criteria

The type of stability used for this particular analysis is Bounded Input Bounded Output (BIBO) stability. Per reference [23], "A system is stable if every bounded input excites a bounded output. Otherwise the system is said to be unstable." A system is determined to be stable if no poles of the open-loop transfer function are located in the open right-hand s-plane. Referring back to Equation 76, it is known that h_c is designed to be stable through the placement of poles far in the left-hand s-plane with the effective PID (multi-loop) controller. The filter transfer function (h_f) is also always BIBO stable (it is a strictly passive network); therefore, the product of these two terms will conversely be BIBO stable. As a result of this, stability of the overall system can be determined by analyzing the denominator of Equation 76 using the Nyquist stability theorem. In order for the system to be stable, the Nyquist stability theorem requires that the Nyquist plot of the system encircle the (–1 + 0j) point counter-clockwise the number of times equal to the number of poles in the open right-hand s-plane. Since there are no system poles in the open right-hand s-plane in this case, no encirclements of the (-1 +0j) point should occur. To further ensure that stability exists, the Nyquist plot of the system is confined to the unit circle:

$$\left|\frac{Z_s}{Z_i}\right| < 1 \quad for -\infty < \omega < \infty \tag{88}$$

With these requirements in place, BIBO stability is guaranteed.

4. Evaluation of the Analyzed System

A MATLAB file was written to examine the stability of the system using various filter parameters. This code is included in Appendix E. The Nyquist plot using the hard switching model together with filter parameters $L_{filter} = 0.5\ mH$ and $C_{filter} = 8265\ \mu F$, and a source resistance estimated at $R_{source} = 0.01\,\Omega$ is shown in Figure IV-4. It can be

seen that the Nyquist contour is positioned within the unit circle. An examination of the poles shows that there are no open right-hand s-plane poles. It is then confirmed to be BIBO stable.

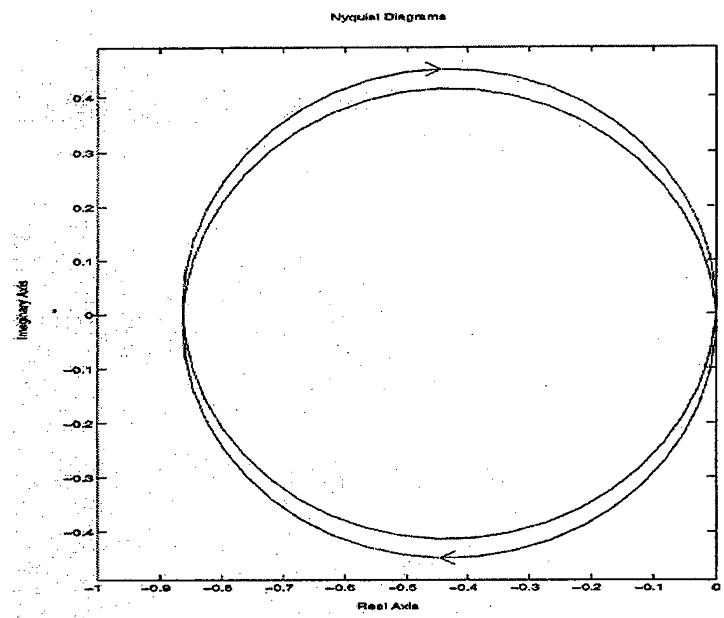

Figure IV-4 Nyquist Plot of BIBO Stable System

The result of lowering the filter capacitor to 6000 μF is shown in Figure IV-5. The Nyquist contour encircles (-1 +0j) twice now. There are still no right-hand s-plane poles; therefore, BIBO stability is not assured.

A noteworthy anomoly was encountered as a result of the method used to calculate the controlled converter's poles and zeros. There exists a pole-zero cancellation that initially seemed not to occur. In fact, it appeared that the system had a RHP pole. Further investigation revealed that the cause was roundoff errors induced over multiple intermediate steps in the calculations.

To this point, two small-signal models have been evaluated to establish stability criteria for the dc link filter. In the next chapter, Lyapunov-based large-signal stability contraints are applied to a basic system model.

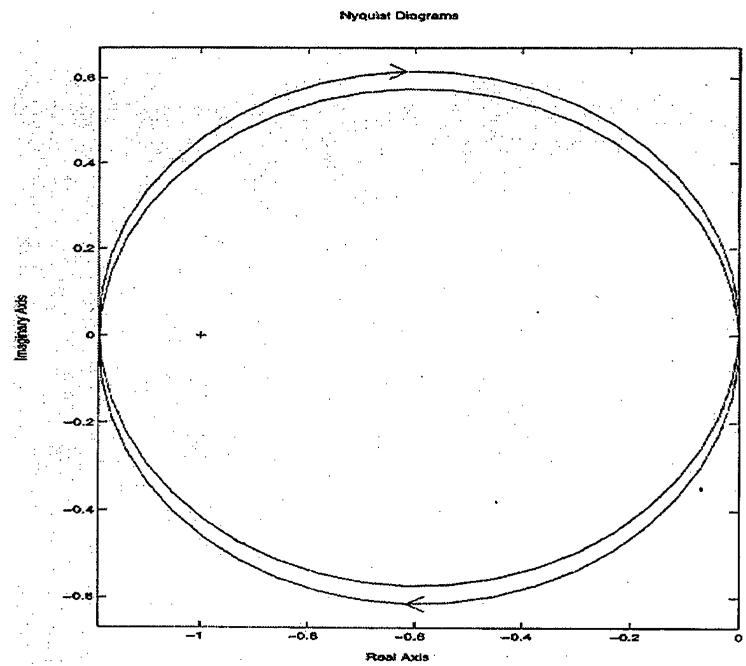

Figure IV-5 Nyquist Plot of Non-BIBO Stable System

V. LYAPUNOV-BASED LARGE-SIGNAL STABILITY CONSTRAINTS

The previous stability criterion, specifically the small-signal models, apply to small disturbances in the system. In Reference [21], the authors examine a stricter set of criteria which act to bound the source resistance for a given set of filter, source voltage, and load power parameters. They note that when small-signal models are used, the stability margins that are used for the final design are forced to be very conservative to ensure stability during a large disturbance. The two criteria specifically examined are the equilibrium point criterion and the mixed potential criterion. This thesis then applies these criteria to representative values being considered for the DC ZEDS project.

A. EQUILIBRIUM POINT CRITERION

The system examined is the same as in Figure III-1. Equations (43) and (44) are the equations that describe the states of the system. The equilibrium points of these equations are found by setting the derivatives of i_r and v_{dci} with respect to time to zero:

$$V_{dci} = \left(\frac{V_{es}}{2}\right)^2 \pm \sqrt{\left(\frac{V_{es}}{2}\right)^2 - R_e P^*} \tag{89}$$

and

$$I_r = \frac{P^*}{V_{dci}} \tag{90}$$

where capital letters are used to distinguish steady-state quantities from instantaneous values.

In order for the above equilibrium points to be stable, they must be positive and real. For the v_{dci} operating point to be real, $R_e P^*$ must be smaller than the $\left(\frac{V_{es}}{2}\right)^2$ term. This results in the condition:

$$R_e < \frac{V_{es}^2}{4P^*} \tag{91}$$

The authors in [21] argue that since this is a hard requirement, it is prudent to apply a safety factor of two when using this criteria. The combined source-filter resistance must satisfy:

$$R_{e,m\arg} < \frac{V_{es}^2}{8P^*} \tag{92}$$

B. MIXED POTENTIAL CRITERION (SINGLE CONSTANT POWER LOAD)

The authors next examine the mixed potential criterion, which was originally developed specifically for non-linear systems. The following mixed potential equation is found using the same system as that used for the equilibrium point criterion:

$$U = -\frac{1}{2}R_e i_r^2 + \int \frac{P^*}{v_{dci}} dv_{dci} + i_r(v_{es} - v_{dci}) \tag{93}$$

Lyapunov-based stability conditions are then placed on this system which results in the following requirement to ensure that the system response to a large disturbance is not oscillatory [see 21]:

$$R_e > \sqrt{\frac{L_e}{C_e}} \tag{94}$$

Since this is not a hard value, no safety margin is required for this criteria. Thus, the design specification on the source plus filter resistance combines Equations (92) and (94) to yield:

$$\sqrt{\frac{L_e}{C_e}} < R_e < \frac{V_{es}^2}{8P^*} \tag{95}$$

Thus, a low equivalent source resistance is attractive from the standpoint of regulation and efficiency, but it in turn may require a large C_e to ensure system stability.

The limitation of this analysis is that a fairly simple representation of the converter is still employed. In particular, little can be deduced as to the impact of control bandwidth on the stability conditions. Also, it relies on a very basic representation of the synchronous machine and rectifier. Since the criteria does not guarantee a stability margin, simulation must be used to assess transient response characteristics. The attendent simplicity, however, does provide a convenient, simple tool which can be used to provide baseline conclusions.

C. MIXED POTENTIAL CRITERION (MULTIPLE CONSTANT POWER LOADS)

In the dc power distribution system envisioned for DD-21, there are multiple converters and loads, each with their own link filters, operating in parallel supplied by the same source. This may represent a generator-rectifier supplying a dc bus which, in turn, delivers power to the various zones within the ship through separate regulated dc-dc converters with associated input filters. It is important to understand how the additional converters affect the constraints placed on the filter design. The system representation of a multiple constant power load system is shown in Figure V-1. The operating point criterion is applied to this configuration to yield:

$$R_e < \frac{V_{es}^2}{4(P1 + P2 + P3)} \tag{96}$$

For simplicity, the case is considered where each of the filters and constant power loads are identical, therefore $L_1 = L_2 = L_3 = L$, $C_1 = C_2 = C_3 = C$, and $P1 = P2 = P3 = P$. Then the Lyapunov stability criterion requires establishing bounds on the norm of [see 21]:

$$K = \frac{-\sqrt{L}}{R_e\sqrt{C}}\begin{bmatrix} 1 & -2 & 2 \\ 0 & 1 & -2 \\ 0 & 0 & 1 \end{bmatrix} \tag{97}$$

If an upperbound of the norm of K is constrained to be less than unity for stability, the following relationship for source resistance holds:

$$R_e > \frac{\sqrt{L}}{\sqrt{C}}\sqrt{2n^2 - n} \qquad (98)$$

where n is the number of converters. For the case of three converters illustrated in Figure V-1:

$$R_e > \frac{\sqrt{L}}{\sqrt{C}}\sqrt{15} \qquad (99)$$

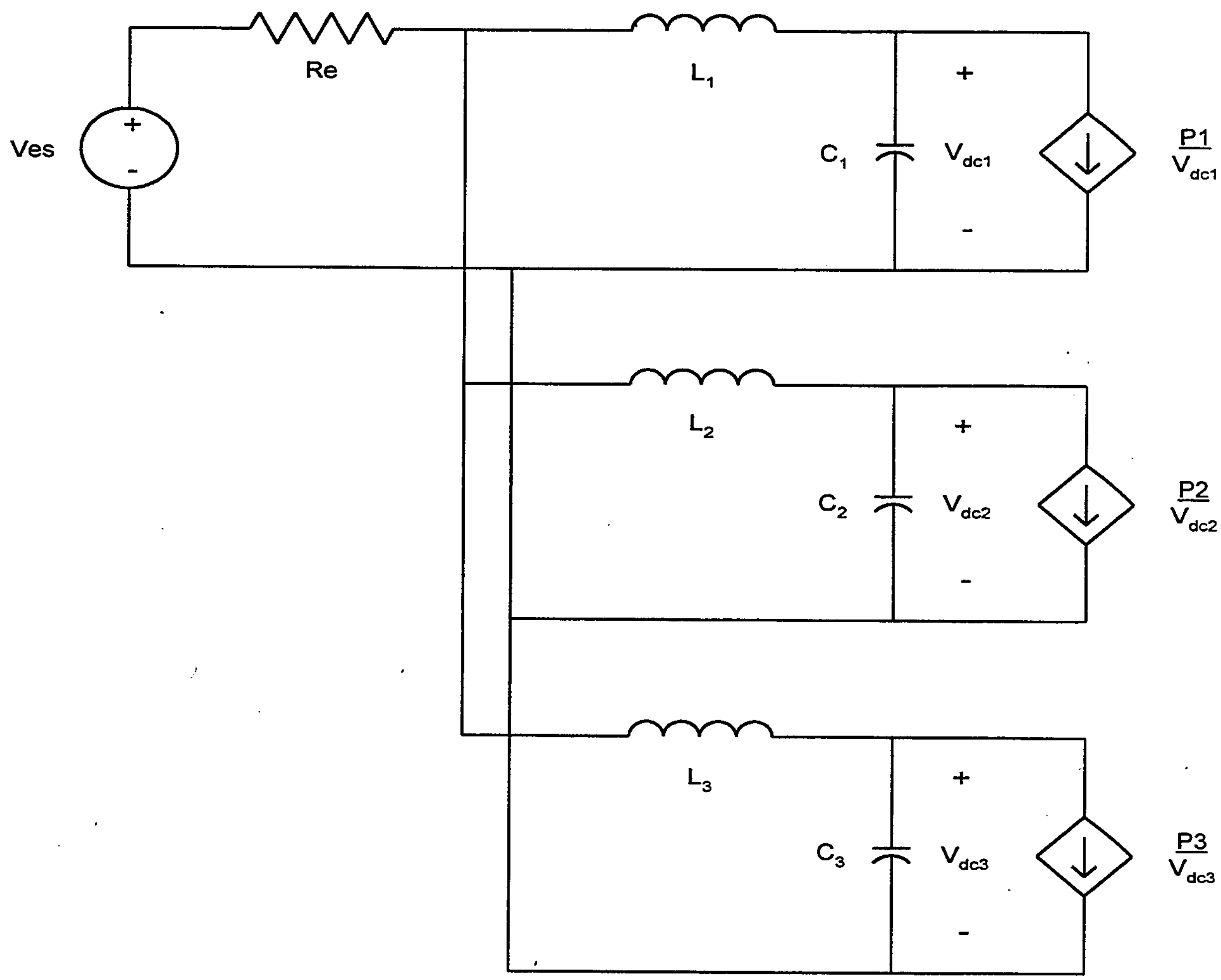

Figure V-1 Multiple Constant Power Load System Representation

Thus, for three identical converters, the source resistance must satisfy:

$$\frac{\sqrt{L}}{\sqrt{C}}\sqrt{15} < R_e < \frac{V_{es}^2}{12P} \tag{100}$$

where no margin has been assumed on the upper bound in Equation (100).

D. EVALUATION OF THE LARGE SIGNAL CRITERIA

The ACSL code of a single load system is contained in Appendix F. Several simulations of the system were conducted to verify the validity of the mixed potential and equilibrium point criteria. The values used for the simulation were $P^* = 200$ kW, $v_{es} =$ 1100V, $L_e = 0.5$ mH, and $C_e = 8265$ μF. These parameters result in boundaries for R between 0.2460 Ω and 1.5125 Ω. When an R of 0.017 Ω is used, which is below the lower limit defined by the mixed potential criterion, it can be seen in Figure V-2 and Figure V-3 that the system is stable for a small 5% disturbance in the system voltage but is unstable for a large 25% disturbance in the system voltage. In both figures, the disturbance is introduced at time 0.5 seconds. The initial transients are due to the system reaching steady-state from the initial simulation conditions, which were approximated to be close to the anticipated steady-state values.

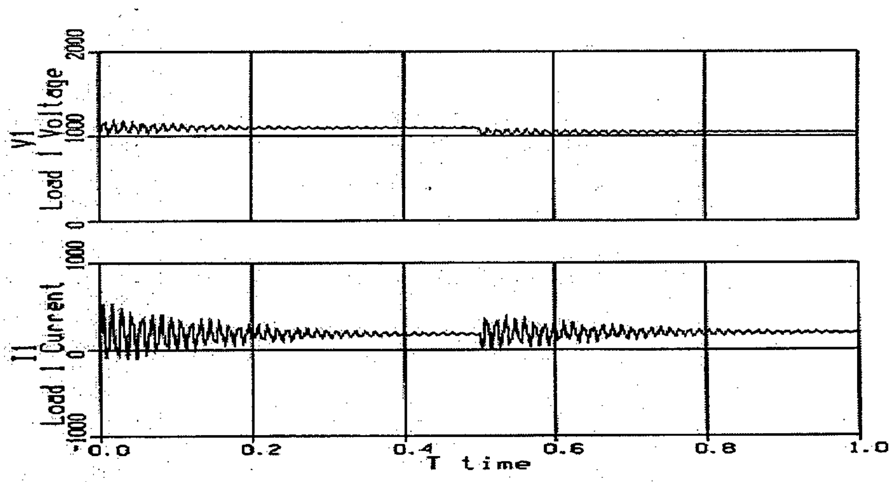

Figure V-2 System Response With R=0.017 Ohms, 5% Drop

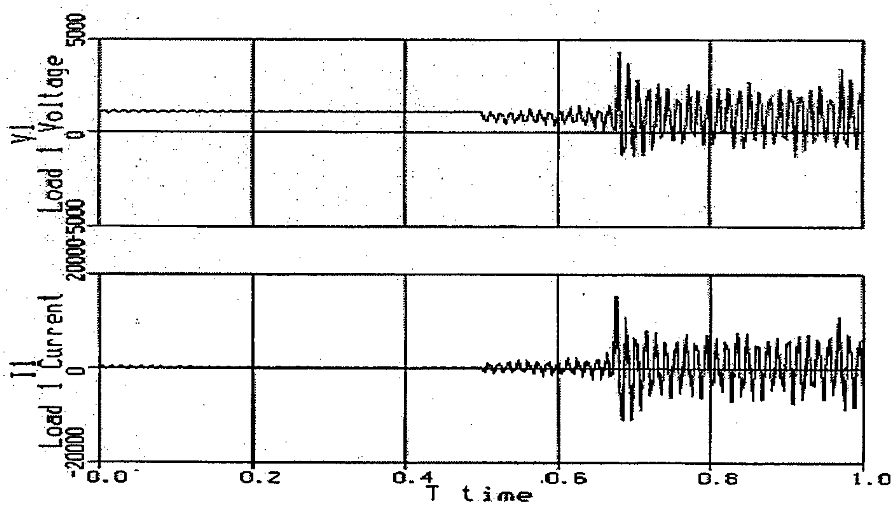

Figure V-3 System Response With R=0.017 Ohms, 25% Drop

Likewise, when a value for R of 0.26 Ω is used, it can be seen in Figure V-4 and Figure V-5 that the system is stable for both small (5%) and large (25%) disturbances in the system voltage. Like the previous simulations, in both figures, the disturbance is introduced at time 0.5 seconds. The initial transients are again due to the system reaching steady-state from the initial simulation conditions, which were approximated to be close to the anticipated steady-state values.

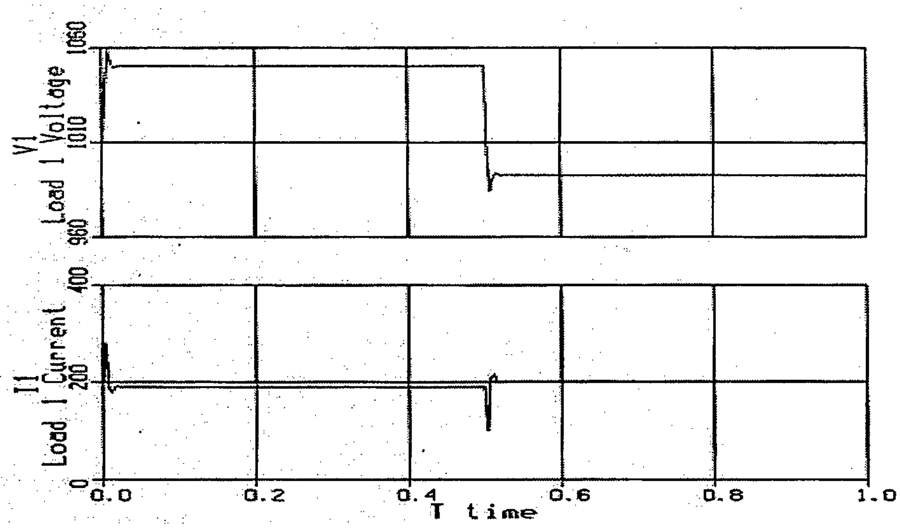

Figure V-4 System Response With R=0.26 Ohms, 5% Drop

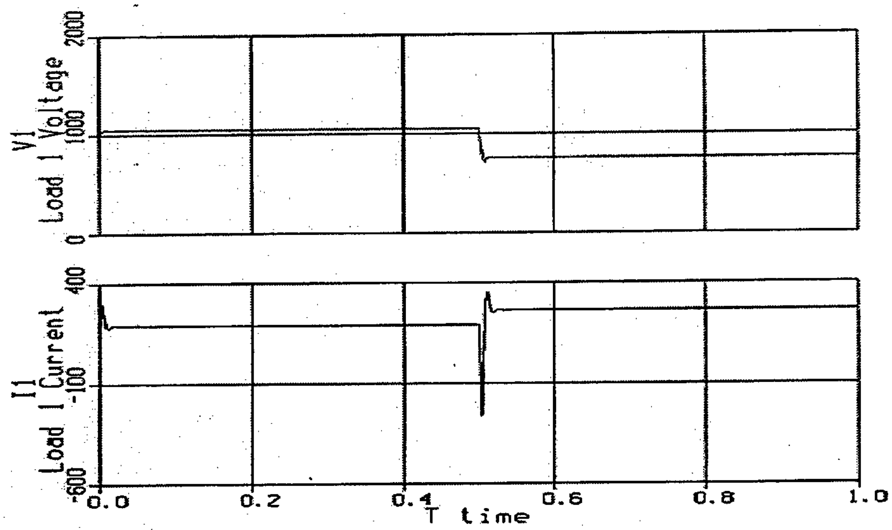

Figure V-5 System Response With R=0.26 Ohms, 25% Drop

VI. INTEGRATED SYSTEM REPRESENTATION

A. USEFULNESS OF AN INTEGRATED SYSTEM

The models used to analyze the stability criteria were all limited in scope to varying degrees due to necessary simplifying assumptions. A more detailed model of the system under consideration would be useful to verify the validity of stability criteria established by different methods. Models of both the synchronous generator-phase controlled rectifier pair and the filter-converter pair have been presented earlier in this thesis. While useful, these models are also limited in that the dynamics of the load are not experienced in the generator-rectifier model and the dynamics of the source are not experienced in the filter-converter model.

B. INTEGRATED SYSTEM MODEL

A circuit diagram of the system modeled by the ACSL file contained in Appendix G is shown in Figure VI-1. A block diagram of the model which clearly shows the various subsystems represented in the model and the interaction of the system parameters between the subsystems is shown in Figure VI-2. The four main subsystems represented in the model are the synchronous machine and rectifer, the generator field regulator, the link filter and the dc-dc converter. The synchronous generator/rectifier section is based on the equations derived in Chapter II. With a dynamic system model, the need for voltage control of the generator becomes evident. The derivations for the equations which govern the synchronous machine voltage regulation are contained in Appendix B. The link filter and dc-dc converter section is identical to that discussed in Chapter IV. Of interest is the fact that the synchronous generator/rectifier/regulator portions are modeled in per unit parameters, while the filter/converter portions are modeled in actual

component parameters. This is accounted for in the code by utilizing conversion factors on the system variables passed between the two sections.

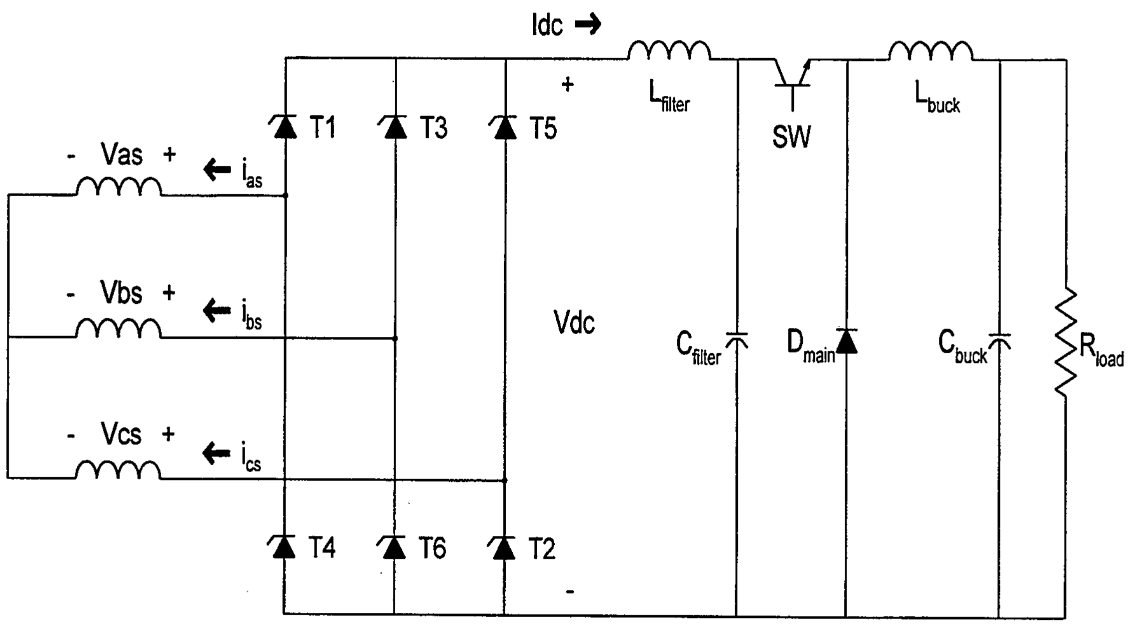

Figure VI-1 Circuit Diagram of Integrated System

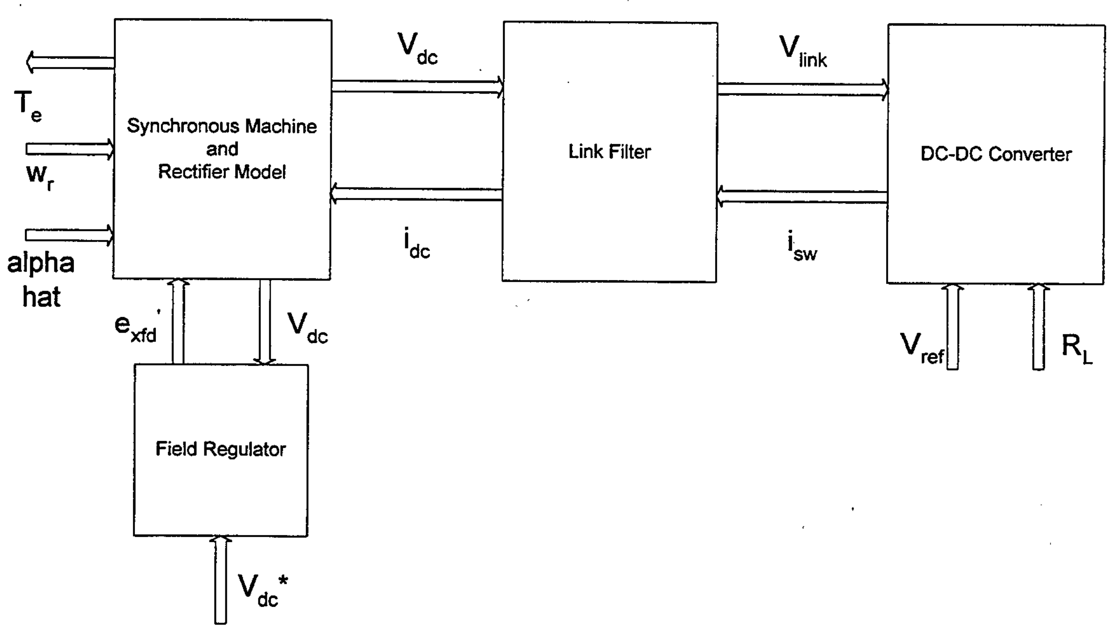

Figure VI-2 Block Diagram of Integrated System

Several simulations were run using the model to verify the validity of both the model and the design criteria evaluated in this thesis. The results of an up-power transient from 10% rated power to 100% rated power at time 0.52 seconds and the subsequent down-power transient back to 10% rated power at time 0.57 seconds are shown in Figure VI-3. The system's component values were all such that the various stability requirements were met. It is shown that the system response is stable and has an acceptable response time.

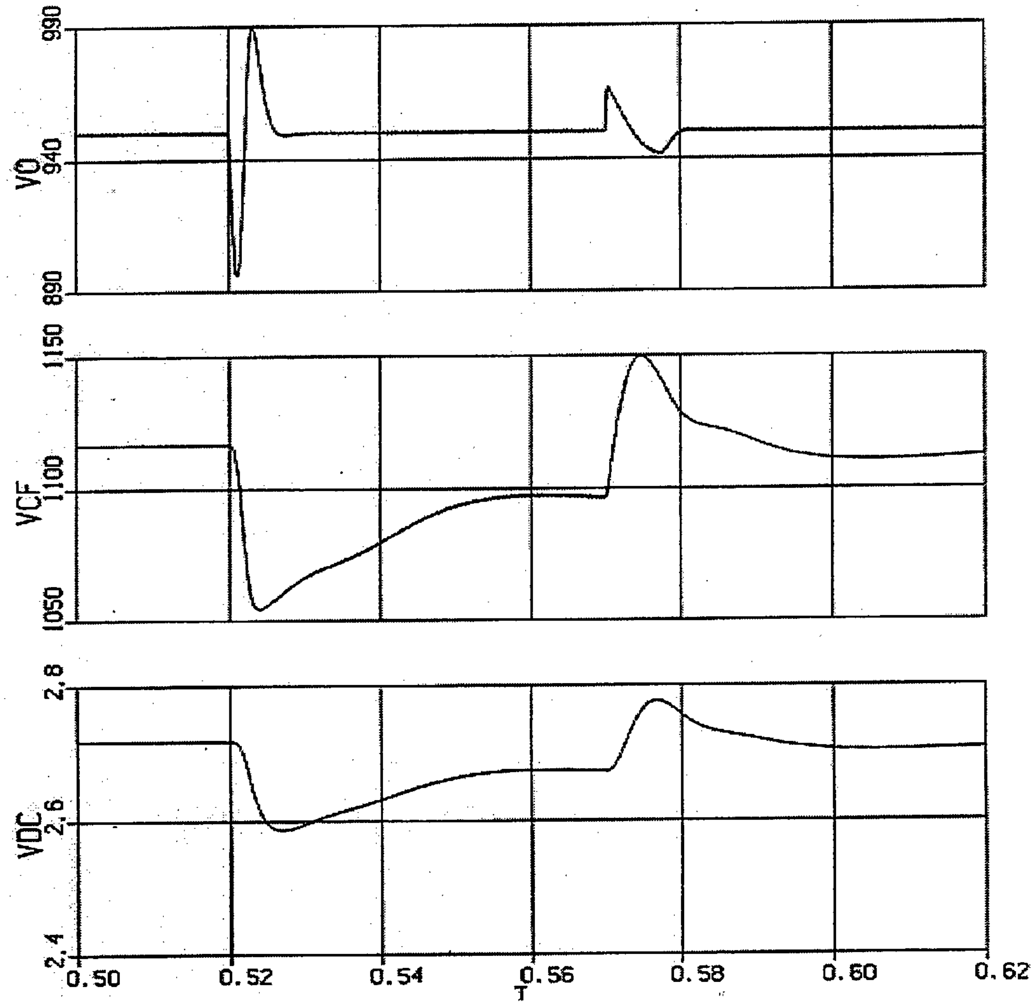

Figure VI-3 Up-Power, Down-Power Transient, Cf = 8265 uF

The same up-power, down-power transient with the filter capacitor value changed to 400 μF is shown in Figure VI-4. While this value of capacitance is enough to maintain stability at the 10% rated power level, it is not sufficient to maintain stability at 100% rated power. This is confirmed by the stability criterion presented in earlier chapters. Large, sustained oscillations are obtained on the dc bus. It is important to note that the dc-dc converter controller maintains the load voltage at the desired reference voltage even with the sustained oscillations present at the converter input.

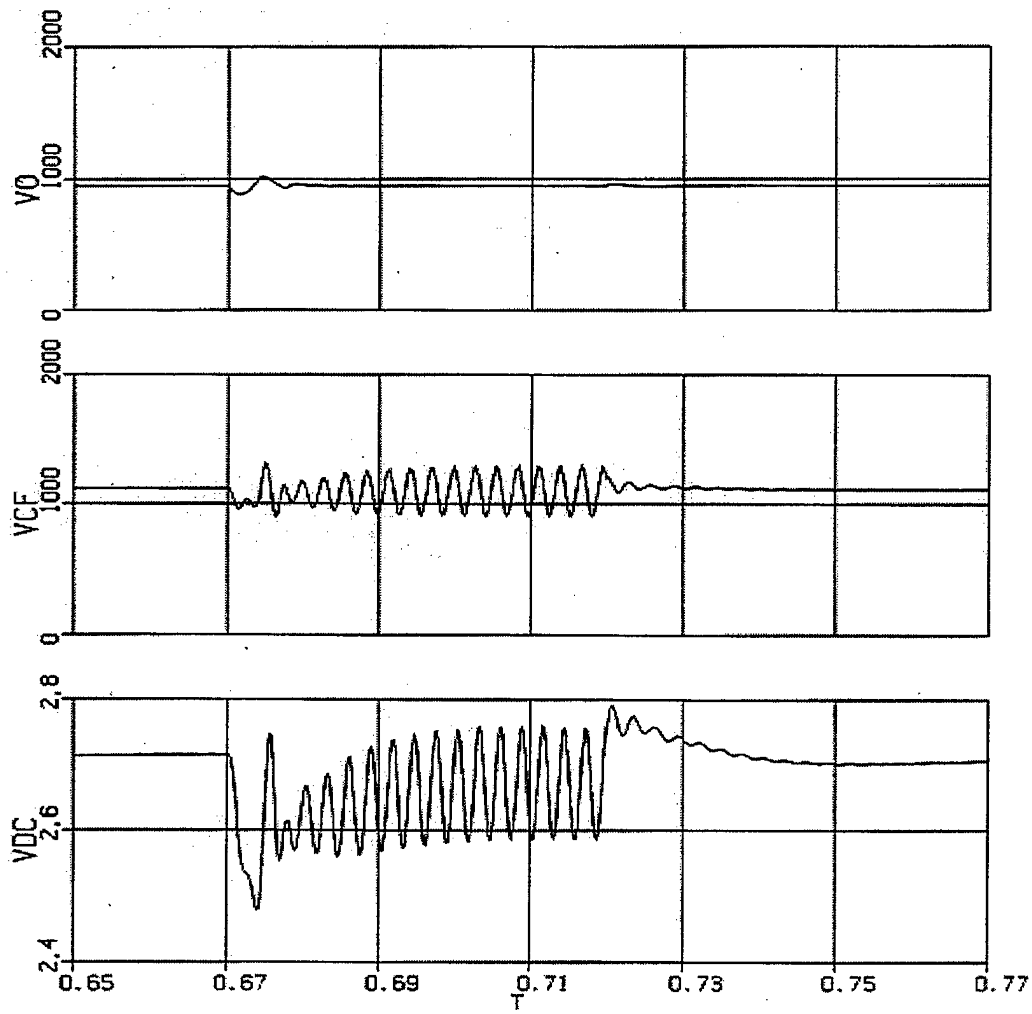

Figure VI-4 Up-Power, Down-Power Transient, Cf = 400 uF

A couple of nuances that were encountered while conducting these system studies deserve further investigation. First, optimization of the numerical integration time step should be performed to uncover at what point the system becomes numerically unstable and at what point it becomes inaccurate. Further, the steady-state duty cycle did not appear to settle at the anticipated value of 0.88. It seemed to hone in on a value approximately 5% higher. This anomoly should be explained. Third, the filter current should be bounded so that there are no occasions when it can go negative. Finally, the voltage/current scaling procedure should be replaced by a more methodical scheme.

The ACSL model of the representative system has been shown to be a useful tool to verify the results of stability analyses conducted by any method. The next chapter will present a summary of the findings of this thesis and discuss future work that can be performed to futher knowledge about this issue.

VII. CONCLUSIONS

A. SUMMARY OF FINDINGS

Two small-signal models and a large-signal model of a representative dc electric power distribution system are examined to determine the design criteria for the dc link filter in the system. The Lyapunov-based large-signal stability criterion is found to be the most conservative of the three analyzed. The next most conservative is the simplified dc link model with the Hurwitz criteria for stability applied. The least conservative is the application of the Nyquist criteria to the impedance-based model. Simulations of the different simplified models were used to illustrate the validity of the filter design limitations defined by each criterion.

When component values that meet the simplified model stability criteria examined are used, detailed model simulations show that these criteria are conservative enough to be considered valid for hardward design. A supplemental finding worthy of comment is the region of stability outside of the criteria bounds established upon investigation of the detailed filter-converter model. The region exists as a result of the feedback controller utilized by the converter to control the duty cycle.

B. FUTURE WORK

This thesis motivates the investigation of other more detailed aspects of stability concerns in a DC ZEDS design. First, further investigation into the stability concerns involved with operating multiple controlled converters in parallel can be undertaken. The simplified models used in this thesis ignored the effects of controlled converters. The relationship between control bandwidth and stability should be investigated. An additional issue is raised when the load on the dc system is an inverter vice a converter.

The input characteristics of a tightly-regulated inverter differ from those of a dc-dc converter.

This thesis has focussed on meeting the system stability requirements by proper selection of the passive components in the device input filters. Further study should be performed with regards to introducing nonlinear compensators into the system. These compensators would preclude the need for large capacitor banks which are both difficult to troubleshoot and have marginal reliability. Finally, the active compensation techniques may be applied to the synchronous machine field regulator, the bus voltage phase-controlled rectifier, or with regards to the dc-dc converter controls. Many research opportunities are currently available in this area and should be explored.

Factors that were assumed negligible in this thesis that may need to be examined in the future include the effects of line inductance and parasitic capacitance in a full size system. Additionally, the effects of electro-magnetic interference (EMI) due to the high switching frequencies used in the converters was not considered.

In conclusion, various stability criteria have been examined to address the stability issues involved with having link filters as an integral part of a dc electrical distribution system. The analysis and tools crafted in this thesis form a strong foundation for establishing design specifications for the L-C filters in the DC ZEDS program.

APPENDIX A: SYNCHRONOUS MACHINE – RECTIFIER ACSL MODEL

A. .CSL FILE

```
PROGRAM             !"tues.csl"

             !"Greg Greseth, LT, USN  -  8 Jan 99"
             !"Last Revised  -  15 Feb 99
             !"This ACSL file simulates a reduced order model for a
synchronous"
             !"machine and three phase rectifier.  The machine parameters
are"
             !"defined in 'per unit' values."

      INITIAL           !"Section in which constants and program
parameters are defined"

             ALGORITHM ialg = 5                  !"Runge-Kutta 4th order"
             CONSTANT tstop = 0.5                !"stop time for
integration"
             MAXTERVAL maxt = 1.e-5              !"max integration step
size"
             MINTERVAL mint = 1.e-6              !"min integration step
size"
             CINTERVAL cint = 5.e-4              !"data communication
interval"

             CONSTANT wb = 377.
             CONSTANT rkqpri = 0.0613
             CONSTANT rkdpri = 0.24
             CONSTANT rfdpri = 0.00111
             CONSTANT J = 1.
             CONSTANT Tl = 1.
             CONSTANT B = 0.
             CONSTANT P = 2.                     !"number of poles"
             CONSTANT Xls = 0.08
             CONSTANT Xmq = 1.00
             CONSTANT Xlkqpri = 0.330
             CONSTANT Xmd = 1.77
             CONSTANT Xlfdpri = 0.137
             CONSTANT Xlkdpri = 0.334
             CONSTANT rs = 0.00515
             CONSTANT exfd = 1.                  !"2.15"
             !"CONSTANT beta = 0.523599"
             !"CONSTANT alpha = 0."
             CONSTANT alfahat = 0.0
             CONSTANT dcI =   0.0                !"0.9"
             CONSTANT PI = 3.141593
             CONSTANT rad120 = 2.094395
             CONSTANT rad60 = 1.047198
             CONSTANT rad30 = 0.523599
```

```
            u = 0.05     !"initialize u for use in first findu function
call"

            !"define the subtransient reactances"

            Xqpripri = Xls+(Xmq*Xlkqpri)/(Xlkqpri+Xmq)
            Xdpripri =
Xls+(Xmd*Xlfdpri*Xlkdpri)/(Xmd*Xlfdpri+Xmd*Xlkdpri&
+Xlkdpri*Xlfdpri)

            Vfdpri = (exfd*rfdpri)/Xmd

            COMMON / forsub /
rad30,rad60,rad120,Xqpripri,Xdpripri,dcI,PI

      END          !"of initial section"

      DYNAMIC

            TERMT(t.ge.tstop, 'Termination on time limit')

            DERIVATIVE

                  !"state equations for psikqpri, psikdpri, psifdpri, wr
and thetar"

                  psikqpri = INTEG(-wb*rkqpri*ikqpri, 0.0)   !"0.049"

                  psikdpri = INTEG(-wb*rkdpri*ikdpri, 1.0)   !"0.293"

                  psifdpri = INTEG(-wb*rfdpri*ifdpri+wb*Vfdpri, 1.077)
      !"0.460"

                  !"wrm = INTEG(((1./J)*(Te-Tl-B*wrm)), 0.)"

                        !"relationship between wrm and state wr

                        !"wr = (P/2.)*wrm"
                        wr = 377.

                  thetar = INTEG(wr, 0.)

                  !"thetar = mod(theta,rad60) + rad60d"

                  !"electrical torque equation"

                  !"Te = ((3./P)/(4.*wb))*(psidsr*iqsr-psiqsr*idsr)"
                  Te = psidsr*iqsr-psiqsr*idsr

                  !"solve first for ikdpri, ifdpri and ikqpri"

                  ikdpri = (1./((Xlkdpri+Xmd)*(Xlfdpri+Xmd)-
Xmd**2.))*((Xlfdpri+Xmd)&
*(psikdpri-Xmd*idsr)-Xmd*(psifdpri-Xmd*idsr))
```

```
                    ifdpri = (1./((Xlkdpri+Xmd)*(Xlfdpri+Xmd)-Xmd**2.))*(-
Xmd*(psikdpri&
-Xmd*idsr)+(Xlkdpri+Xmd)*(psifdpri-Xmd*idsr))

                    ikqpri = psikqpri/(Xlkqpri+Xmq)-
(Xmq*iqsr)/(Xlkqpri+Xmq)

                    !"equations to eliminate psiqsr and psidsr"

                    psiqsr = Xqpripri*iqsr+psiqpripri

                    psidsr = Xdpripri*idsr+psidpripri

                    !"define the subtransient flux linkages"

                    psiqpripri = (Xmq/(Xmq+Xlkqpri))*psikqpri

                    psidpripri =
((Xmd*psikdpri)/Xlkdpri+(Xmd*psifdpri)/Xlfdpri)&
/(1.+Xmd/Xlfdpri+Xmd/Xlkdpri)

                    !"define Eqpripri and Edpripri"

                    Eqpripri = (wr*psidpripri)/wb

                    Edpripri = -(wr*psiqpripri)/wb

                    !"define phi to use to determine alpha"

                    phi = ATAN2(Edpripri,Eqpripri)

                    !"call function to determine beta"

                          beta = findbeta(psidpripri,psiqpripri,alfahat)

                    !"define alpha"

                    alpha = beta - phi

                    !"desired reduced order voltage-behind-reactance
equations"

                    Vqsr = rs*iqsr+(wr/wb)*Xdpripri*idsr+Eqpripri

                    Vdsr = rs*idsr-(wr/wb)*Xqpripri*iqsr+Edpripri

                    !"equation for average DC voltage out of rectifier"

                    Vdc = (3.*sqrt(3.)/PI)*(wr/wb)*(sqrt(psiqpripri**2&
+psidpripri**2))*(cos(alpha))-
(3./PI)*(wr/wb)*(((Xqpripri+Xdpripri)/2.)*dcI&
+(Xdpripri-Xqpripri)*dcI*sin(2.*beta+rad30))

                    !"need to define K1 for use in subroutines"

                    Kone = sqrt(3.)*(-
psiqpripri*sin(beta)+psidpripri*cos(beta))&
```

```
+((Xdpripri-Xqpripri)*cos(2.*beta+rad120)-0.5*(Xqpripri+Xdpripri))*dcI
                    !"call function to determine u using 'half-it' method"
                    u = findu(Kone,psiqpripri,psidpripri)
                    !"now with the new u, we can determine conduction
currents"
                    iqsrcond = ((2.*sqrt(3.))/PI)*dcI*(cos(beta+rad120)&
-cos(beta+u+rad60))
                    idsrcond = ((2.*sqrt(3.))/PI)*dcI*(sin(beta+rad120)&
-sin(beta+u+rad60))
                    !"calculate the commutating currents using Simpson
method"
                    !"first, define the 5 different values of thetar to be
used"
                    thetar1 = beta+rad60
                    thetar2 = beta+rad60+u/4.
                    thetar3 = beta+rad60+u/2.
                    thetar4 = beta+rad60+(3.*u)/4.
                    thetar5 = beta+rad60+u
                    !"call each q and d subroutine 5 times to calculate
components"
                    PROCEDURAL (Q1 = thetar1,Kone,psiqpripri,psidpripri)
                          CALL
simpsonq(thetar1,Kone,psiqpripri,psidpripri,Q1)
                    END   !"of procedural"
                    PROCEDURAL (D1 = thetar1,Kone,psiqpripri,psidpripri)
                          CALL
simpsond(thetar1,Kone,psiqpripri,psidpripri,D1)
                    END   !"of procedural"
                    PROCEDURAL (Q2 = thetar2,Kone,psiqpripri,psidpripri)
                          CALL
simpsonq(thetar2,Kone,psiqpripri,psidpripri,Q2)
                    END   !"of procedural"
                    PROCEDURAL (D2 = thetar2,Kone,psiqpripri,psidpripri)
```

```
                    CALL
simpsond(thetar2,Kone,psiqpripri,psidpripri,D2)

              END   !"of procedural"

              PROCEDURAL (Q3 = thetar3,Kone,psiqpripri,psidpripri)

                    CALL
simpsonq(thetar3,Kone,psiqpripri,psidpripri,Q3)

              END   !"of procedural"

              PROCEDURAL (D3 = thetar3,Kone,psiqpripri,psidpripri)

                    CALL
simpsond(thetar3,Kone,psiqpripri,psidpripri,D3)

              END   !"of procedural"

              PROCEDURAL (Q4 = thetar4,Kone,psiqpripri,psidpripri)

                    CALL
simpsonq(thetar4,Kone,psiqpripri,psidpripri,Q4)

              END   !"of procedural"

              PROCEDURAL (D4 = thetar4,Kone,psiqpripri,psidpripri)

                    CALL
simpsond(thetar4,Kone,psiqpripri,psidpripri,D4)

              END   !"of procedural"

              PROCEDURAL (Q5 = thetar5,Kone,psiqpripri,psidpripri)

                    CALL
simpsonq(thetar5,Kone,psiqpripri,psidpripri,Q5)

              END   !"of procedural"

              PROCEDURAL (D5 = thetar5,Kone,psiqpripri,psidpripri)

                    CALL
simpsond(thetar5,Kone,psiqpripri,psidpripri,D5)

              END   !"of procedural"

              !"now add all the components together"

              iqsrcom = (u/(PI*4.))*(Q1+4.*Q2+2.*Q3+4.*Q4+Q5)

              idsrcom = (u/(PI*4.))*(D1+4.*D2+2.*D3+4.*D4+D5)

              !"add the commutating and conduction components to get
average"
              !"iqsr and idsr"
```

```
                    iqsr = iqsrcom+iqsrcond

                    idsr = idsrcom+idsrcond

              END   !"of derivative"

        END   !"of dynamic"

END   !"of program"
      SUBROUTINE simpsonq(thetarsimp,Kone,psiqpripri,psidpripri,iqsrout)
************************************************************************
*
* subroutine to calculate components for simpson method of determining
* the q commutating currents
*
************************************************************************
      COMMON / forsub / rad30,rad60,rad120,Xqpripri,Xdpripri,dcI,PI
*
* declare variables
*
      real ias, part1, part2, part3, Kone, iqsrout, dcI
*
* break the equation for ias down into manageable parts
*
      part1=Kone-sqrt(3.)*(psiqpripri*cos(thetarsimp+rad30)+psidpripri
     +      *sin(thetarsimp+rad30))
*
      part2=(Xqpripri-Xdpripri)*cos(2.*thetarsimp+rad60)+Xqpripri
     +      +Xdpripri
*
      part3=((Xqpripri-Xdpripri)*cos(2.*thetarsimp+rad120)+0.5
     +      *(Xqpripri+Xdpripri))*dcI
*
* combine the 3 parts to determine ias
*
      ias=(part1/part2)-(part3/part2)
*
* now solve for iqsr at the inputed thetar
*
      iqsrout=((2.*sqrt(3.))/3.)*(ias*cos(thetarsimp+rad30)-dcI
     +        *sin(thetarsimp))
*
      end
      SUBROUTINE simpsond(thetarsimp,Kone,psiqpripri,psidpripri,idsrout)
************************************************************************
*
* subroutine to calculate components for simpson method of determining
* the d commutating currents
*
************************************************************************
      COMMON / forsub / rad30,rad60,rad120,Xqpripri,Xdpripri,dcI,PI
*
* declare variables
*
      real ias, part1, part2, part3, Kone, idsrout, dcI
*
* break the equation for ias down into manageable parts
```

```
*
      part1=Kone-sqrt(3.)*(psiqpripri*cos(thetarsimp+rad30)+psidpripri
     +      *sin(thetarsimp+rad30))
*
      part2=(Xqpripri-Xdpripri)*cos(2.*thetarsimp+rad60)+Xqpripri
     +      +Xdpripri
*
      part3=((Xqpripri-Xdpripri)*cos(2.*thetarsimp+rad120)+0.5
     +      *(Xqpripri+Xdpripri))*dcI
*
* combine the 3 parts to determine ias
*
      ias=(part1/part2)-(part3/part2)
*
* now solve for idsr at the inputed thetar
*
      idsrout=((2.*sqrt(3.))/3.)*(ias*sin(thetarsimp+rad30)+dcI
     +        *cos(thetarsimp))
*
      end
      REAL FUNCTION findu(Kone,psiqpripri,psidpripri)
**********************************************************************
*
* function subprogram to calculate u using the 'half-it' method
*
**********************************************************************
      COMMON / forsub / rad30,rad60,rad120,Xqpripri,Xdpripri,dcI,PI
*
* declare variables to be used
*
      logical condition
      real utemp, fcom, fpricom, Kone, dcI, u1, u2, u
*
      u1=0.0
      u2=rad60
      u=0.0
      fcom=Kone-sqrt(3.)*(-psiqpripri*sin(beta+u)+psidpripri
     +     *cos(beta+u))-((Xqpripri-Xdpripri)*cos(2.*beta+2.*u
     +     -rad120)+0.5*(Xqpripri+Xdpripri))*dcI
10    if (ABS(u1-u2) .gt. 0.001) then
         u = 0.5*(u1+u2)
         fcom=Kone-sqrt(3.)*(-psiqpripri*sin(beta+u)+psidpripri
     +        *cos(beta+u))-((Xqpripri-Xdpripri)*cos(2.*beta+2.*u
     +        -rad120)+0.5*(Xqpripri+Xdpripri))*dcI
         if (fcom .le. 0.00) then
            u1=u
         else
            u2=u
         endif
         goto 10
      endif
      findu=u
      END
      REAL FUNCTION findbeta(psidpripri,psiqpripri, alfahat)
**********************************************************************
*
* function subprogram to calculate beta
```

```
*
************************************************************************
      COMMON / forsub / rad30,rad60,rad120,Xqpripri,Xdpripri,dcI,PI
*
* declare variables to be used
*
      real betatop, betabot, betamin, alfahat, fbmin
*
      betatop = PI
      betabot = -PI
      betamin = 0.0
*
* calculate the function to determine if beta is greater than betamin
*
      fbmin = SQRT(3.)*(psiqpripri*cos(betamin)+psidpripri*sin(betamin))
     +        +2.*dcI*(Xqpripri-Xdpripri)*sin(2.*betamin-rad60)
10    if (ABS(betatop-betabot) .gt. 0.001) then
         betamin = (betatop+betabot)/2.
         fbmin = SQRT(3.)*(psiqpripri*cos(betamin)+psidpripri
     +        *sin(betamin))+2.*dcI*(Xqpripri-Xdpripri)*sin(2.*betamin
     +        -rad60)
         if (fbmin .le. 0.0) then
            betabot = betamin
         else
            betatop = betamin
         endif
         goto 10
      endif
*
* now determine beta based on the above determination
*
      findbeta = alfahat + betamin
      END
```

B. .CMD FILE

```
!"tues.cmd"

!"Greg Greseth - 15 Feb 1999"
!"This file plot the output of a synchronous generator, phase-
controlled"
!"rectifier model."

s strplt = .t.                 ! "one variable per x-axis"
s calplt = .f.

s devplt = 1                   ! "1 for X-windows"
                         ! "5 for postscript"

s ppoplt = .f.                 ! "true rotates plot 90 deg"

s xinspl = 6                   ! "x-axis plot units"

s weditg = .f.                 ! "false suppresses data write"
```

```
                                ! "each time SCHEDULE occurs"
s wesitg = .f.

s nrwitg = .f.                       ! "true enables accumulation of data"
                                ! "after a CONTIN"

s alcplt = .f.                         ! "false makes all plots dark"

s tstop = 40.

s maxt=1.0e-4

s cint=1.0e-3


prepare
t,Vdc,Te,psikqpri,psikdpri,psifdpri,iqsr,idsr,u,thetar,beta,alpha,phi

PROCED startup
      s ialg=5
        s devplt = 1
      start
        s plt = 1
      plot Vdc,Te,psikqpri,psikdpri
        s plt = 2
        plot psifdpri,iqsr,idsr,u
        s plt = 3
        plot beta, phi, alpha
END

PROCED testalfa
      s tstop = 60
      s ialg=5
      start
        d Vdc,Te,psikqpri,psikdpri,psifdpri,iqsr,idsr,u,beta,phi,alpha
END
```

APPENDIX B: DERIVATION OF SYNCHRONOUS MACHINE VOLTAGE REGULATION

The reduced-order (stator transients ignored) electrical equations of a 3-phase synchrounous machine with a single q and d-axis damper winding may be expressed by:

$$\vec{V}^r_{qds} = \overline{A}\,\vec{i}^{\,r}_{qds} + \overline{B}\,\vec{\Psi}^r_{qds} \tag{B-1}$$

$$\vec{V}'_{qdr} = \overline{C}\,\vec{i}^{\,'}_{qdr} + \overline{D}\frac{d}{dt}\vec{\Psi}'_{qdr} \tag{B-2}$$

$$\vec{\Psi}^r_{qds} = \overline{F}\,\vec{i}^{\,r}_{qds} + \overline{G}\,\vec{i}^{\,'}_{qdr} \tag{B-3}$$

$$\vec{\Psi}'_{qdr} = \overline{H}\,\vec{i}^{\,r}_{qds} + \overline{J}\,\vec{i}^{\,'}_{qdr} \tag{B-4}$$

where:

$$\vec{i}^{\,r}_{qds} = \begin{bmatrix} i^r_{qs} \\ i^r_{ds} \end{bmatrix} \tag{B-5}$$

$$\vec{i}^{\,'}_{qdr} = \begin{bmatrix} i'_{kq} \\ i'_{fd} \\ i'_{kd} \end{bmatrix} \tag{B-6}$$

With the stator currents referenced into the machine and assuming a purely resistive load, the terminal voltages may be expressed solely in terms of the terminal currents:

$$\vec{V}^r_{qds} = \overline{K}\,\vec{i}^{\,r}_{qds} \tag{B-7}$$

where:

$$K = \begin{bmatrix} -R_{load} & 0 \\ 0 & -R_{load} \end{bmatrix} \tag{B-8}$$

Upon substituting (B-7) into (B-1) and solving for $\vec{\Psi}^r_{qds}$, we get:

$$\Psi^r_{qds} = -\overline{B}^{-1}(\overline{A} - \overline{K})\,\vec{i}^{\,r}_{qds} \tag{B-9}$$

Further, (B-9) can be substitued into (B-3) so that the stator currents may be solved for in terms of the rotor currents:

$$\bar{i}^{\,r}_{qds} = \bar{L}\,\bar{i}^{\,'}_{qdr} \tag{B-10}$$

where:

$$\bar{L} = \left[-\bar{B}^{-1}(\bar{A} - \bar{K}) - \bar{F}\right]^{-1}\bar{G} \tag{B-11}$$

Equation (B-10) is then plugged into (B-4) to yield:

$$\bar{\Psi}^{'}_{qdr} = (\bar{H}\,\bar{L} + \bar{J})\,\bar{i}^{\,'}_{qdr} \tag{B-12}$$

and solving for $\bar{i}^{\,'}_{qdr}$:

$$\bar{i}^{\,'}_{qdr} = (\bar{H}\,\bar{L} + \bar{J})^{-1}\,\bar{\Psi}^{'}_{qdr} \tag{B-13}$$

Finally, substituting (B-13) into (B-2), we get:

$$V^{'}_{qdr} = \bar{C}(\bar{H}\,\bar{L} + \bar{J})^{-1}\bar{\Psi}^{'}_{qdr} + \bar{D}\frac{d}{dt}\bar{\Psi}^{'}_{qdr} \tag{B-14}$$

and since $V^{'}_{kq} = V^{'}_{kd} = 0$, the referred rotor voltage vector may be re-expressed as:

$$\bar{V}^{'}_{qdr} = \bar{N}V^{'}_{fd} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} V^{'}_{fd} \tag{B-15}$$

The output of the machine is the terminal voltages. Equations (B-7), (B-10), and (B-13) may be combined to express the terminal voltages in terms of the rotor states:

$$\bar{V}^{r}_{qds} = \bar{K}\,\bar{L}(\bar{H}\,\bar{L} + \bar{J})^{-1}\bar{\Psi}^{'}_{qdr} \tag{B-16}$$

Once we assume that the turbine governor is holding ω_r constant, equations (B-14) and (B-16) become a set of linear ordinary differential equations. However, the peak value of the terminal voltages is related to V^{r}_{qs} and V^{r}_{ds} by:

$$V^{r}_{qds,pk} = \sqrt{(V^{r}_{qs})^2 + (V^{r}_{ds})^2} \tag{B-17}$$

Therefore, to consider a single–input ($V^{'}_{fd}$), single-output ($V^{r}_{qds,pk}$) system, the output relationship must be linearized about an operating point:

$$\Delta V^{r}_{qds,pk} = \bar{M}\,\Delta\bar{V}^{r}_{qds} \tag{B-18}$$

where:

$$\overline{M} = \left[\frac{V_{qso}^{r}}{\sqrt{(V_{qso}^{r})^2 + (V_{dso}^{r})^2}} \quad \frac{V_{dso}^{r}}{\sqrt{(V_{qso}^{r})^2 + (V_{dso}^{r})^2}} \right] \tag{B-19}$$

Finally, the state-space model of the generator is given by:

$$\frac{d}{dt}\Delta\overline{\Psi}_{qdr}^{'} = \overline{A}_2 \Delta\overline{\Psi}_{qdr}^{'} + \overline{B}_2 \Delta V_{fd}^{'} \tag{B-20}$$

$$\Delta V_{qds,pk}^{r} = \overline{C}_2 \Delta\overline{\Psi}_{qdr}^{'} \tag{B-21}$$

where:

$$\overline{A}_2 = -\overline{D}^{-1}\overline{C}(\overline{H}\,\overline{L} + \overline{J})^{-1} \tag{B-22}$$

$$\overline{B}_2 = \overline{D}^{-1}\overline{N} \tag{B-23}$$

$$C_2 = \overline{M}\,\overline{K}\,\overline{L}(\overline{H}\,\overline{L} + \overline{J})^{-1} \tag{B-24}$$

A final point lies in determining the operating point values for (B-19). This can be accomplished assuming that for rated load, $V_{fd}^{'}$ has been selected to provide the rated terminal voltage. In the steady state:

$$\overline{\Psi}_{qdro}^{'e} = -\overline{A}_2^{\,-1}\overline{B}_2 V_{fdo}^{'} \tag{B-25}$$

Substituting (B-25) into the output equation (B-16), we find:

$$V_{qdso}^{r} = -\overline{K}\,\overline{L}(\overline{H}\,\overline{L} + \overline{J})^{-1}\overline{A}_2^{\,-1}\overline{B}_2 V_{fd}^{'} \tag{B-26}$$

or:

$$V_{qdso}^{r} = \overline{A}_3 V_{fd}^{'} \tag{B-27}$$

where $\overline{A}_3$ is a 2-by-1 vector:

$$\overline{A}_3 = \begin{bmatrix} \overline{A}_3(1) \\ \overline{A}_3(2) \end{bmatrix} \tag{B-28}$$

Thus, from (B-17) and (B-27):

$$V_{qds,pk}^{r} = \sqrt{A_3(1)^2 + A_3(2)^2}\; V_{fd}^{'} \tag{B-29}$$

Therefore, for a given load resistance ($\overline{K}$), the appropriate field voltage to give the rated terminal voltage is found from:

$$V'_{fd} = \frac{1}{\sqrt{\overline{A}_3(1)^2 + \overline{A}_3(2)^2}} V^r_{qds,pk,rat} \tag{B-30}$$

This value may then be substitued back into (B-27) to yield the desired operating point values.

At this point, the design of the field regulator can commence. To illustrate the need for compensation, the open-loop eigenvalues of $\overline{A}_2$ from Equation B-20 can be calculated assuming a load resistance of 1.0 pu. These are found to be:

$$\lambda_1 = -19.71$$

$$\lambda_2 = -198.61$$

$$\lambda_3 = -0.54$$

The λ_3 eigenvalue introduces a fairly long recovery time. In addition, open-loop, the operator would need to know the load in order to apply the correct V'_{fd} to maintain the desired $V^r_{qds,pk}$. For instance, with R_{load} = 1.0, the required field voltage to yield $V^r_{qds,pk}$ = 1.0 is:

$$V'_{fd} = 0.0012789$$

or

$$e'_{xfd} = 2.039 = \frac{X_{md}}{r'_{fd}} V'_{fd} \tag{B-31}$$

As the load power is decreased, this excitation voltage must be lowered to maintain $V^r_{qds,pk}$ = 1.0. For the above condition, the required stator voltage operating points are found to be:

$$V^r_{qso} = 0.6813 \text{ pu}$$

$$V^r_{dso} = 0.7320 \text{ pu}$$

The system can be linearized about these operating points and a transfer function derived between $\Delta V'_{fd}$ and $\Delta V^r_{qds,pk}$:

$$G(s) = \frac{\Delta V^{r}_{qds,pk}}{\Delta V'_{fd}} = \frac{219.7(s+271)(s+27.7)}{(s+19.7)(s+199)(s+0.54)} \tag{B-32}$$

The desired control loop is then illustrated in Figure B-1. The circuit can be analyzed to yield the closed-loop transfer function:

$$\frac{\Delta V^{r}_{qds,pk}}{\Delta V^{r*}_{qds,pk}} = \frac{n_c\, n_g}{n_c\, n_g + d_c\, d_g} \tag{B-33}$$

and the steady-state error:

$$E_{ss} = \left. \frac{d_c\, d_g\, V^{r*}_{qds,pk}}{n_c\, n_g + d_c\, d_g} \right|_{s=0} \tag{B-34}$$

where n_c, n_g, d_c and d_g are polynomials in s.

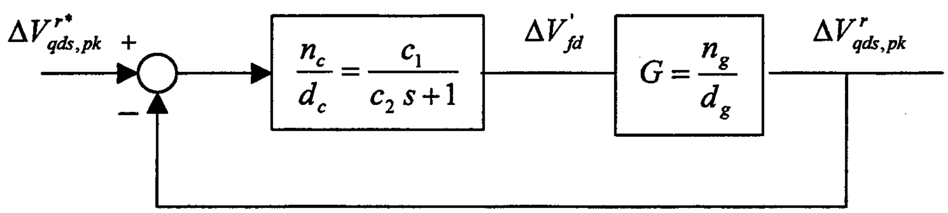

Figure B-1 Field Regulator Control Loop

The control gains c_1 and c_2 must be selected to yield satisfactory steady-state error and acceptable closed-loop pole locations. Plugging in the transfer function elements into Equation B-34 yields:

$$E_{ss} = \frac{1}{1+799\, c_1} \tag{B-35}$$

If the output voltage is to be within 0.5% of the commanded value, this imposes the constraint:

$$c_1 > 0.223 \tag{B-36}$$

If it is assumed that $c_1 = 0.25$ for convenience, c_2 may be selected based on the closed-loop poles of Equation B-33. Note, the zeros of Equation B-33 are fixed by the zeros of n_g and once c_1 is fixed, the steady-state error is fixed. Table B-1 illustrates how the closed-loop poles vary as c_2 is changed.

c_2	Pole 1	Pole 2	Poles 3 & 4
1000	-199	-19.7	$-0.269^+/j0.18$
10	-199	-19.9	$-0.235^+/j3.23$
1	-199	-21.0	$-0.084^+/j9.97$
0.1	-200	-25.1	$-2.06^+/j28.7$
0.01	-212	-30.6	$-38.23^+/j70.23$
0.002	-457	-32.6	$-114^+/j28.3$
0.001	-948	-33	-89.1 & -149

Table B-1 Closed-loop Poles Versus Gain c_2

As the gain is decreased, the poles 3 & 4 move from slow, lightly damped locations to positions comfortably in the left-half plane. An attractive compensator transfer function is given by:

$$\frac{\Delta V_{fd}'}{\Delta V_{qds,pk}^{r*} - \Delta V_{qds,pk}^{r}} = \frac{0.25}{0.002s+1} \tag{B-37}$$

or

$$\frac{\Delta e_{xfd}'}{\Delta V_{qds,pk}^{r*} - \Delta V_{qds,pk}^{r}} = \frac{400}{0.002s+1} \tag{B-38}$$

One final point to understand is that this design is valid for one operating condition ($R_{load} = 1.0$ pu). As illustrated by Table B-2, the steady-state value of e_{xfd}'

must be varied to maintain rated output voltage. The corresponding transfer functions can be evaluated and analyzed for suitability.

R_{load} (pu)	e'_{xfd} (pu)
1.0	2.039
1.2	1.771
1.4	1.601
1.6	1.478
1.8	1.388
2.0	1.321
5.0	1.057
10.0	1.015

Table B-2 Excitation Voltage Required to Yield Rated Output Voltage

APPENDIX C: SIMPLIFIED DC LINK ACSL MODEL

A. NON-LINEAR .CSL FILE

```
PROGRAM              !"simplenonlin.csl"
            !"Greg Greseth - 8 April 1999"

!"This file contains the non-linear system equations for a simplified"
!"DC link model.  The simulated event is a 10%-100%-10% power
transient."


INITIAL

      ALGORITHM ialg = 5
      MAXTERVAL maxt = 1.e-5
      MINTERVAL mint = 1.e-6
      CINTERVAL cint = 5.e-3
      CONSTANT Le = 0.0005
      CONSTANT Ce = 0.008265
      CONSTANT Re = 0.01
      CONSTANT tstop = 5.0
      CONSTANT P = 20000.
      CONSTANT Ves = 1102.

END   !"of initial

DYNAMIC

TERMT(t.ge.tstop, 'Termination on time limit')

      DERIVATIVE

      P_star = P + 180000.*STEP(2.0) - 180000.*STEP(3.5)

      ir = INTEG(-(Vdci/Le)-(Re*ir)/Le+Ves/Le,181.82)

      Vdci = INTEG(ir/Ce-(P_star)/(Ce*Vdci),1100.)

      END   !"of derivative"

END   !"of dynamic"

END   !"of program"
```

B. NON-LINEAR .CMD FILE

```
!"simplenonlin.cmd"
!"Greg Greseth - 8 April 1999"

!"This file plots the inductor current and capacitor voltage"
!"for the non-linear simplified DC link model"

s strplt = .t.                  ! "one variable per x-axis"
s calplt = .f.

s devplt = 1                    ! "1 for X-windows"
                          ! "5 for postscript"

s ppoplt = .f.                  ! "true rotates plot 90 deg"

s xinspl = 6                    ! "x-axis plot units"

s weditg = .f.                  ! "false suppresses data write"
                          ! "each time SCHEDULE occurs"
s wesitg = .f.

s nrwitg = .f.                  ! "true enables accumulation of data"
                          ! "after a CONTIN"

s alcplt = .f.                    ! "false makes all plots dark"

prepare t,ir,Vdci

PROCED nonlinear
      start
            plot ir,Vdci
        END
```

C. LINEAR .CSL FILE

```
PROGRAM             !"simplelin.csl"
            !"Greg Greseth - 8 April 1999"

!"This file contains the linearized system equations for a simplified"
!"DC link model.  The simulated event is a 10%-100%-10% power
transient."

INITIAL

      ALGORITHM ialg = 5
      MAXTERVAL maxt = 1.e-5
      MINTERVAL mint = 1.e-6
      CINTERVAL cint = 5.e-3
      CONSTANT Le = 0.0005
      CONSTANT Ce = 0.008265
```

```
      CONSTANT Re = 0.01
      CONSTANT tstop = 1.5
      CONSTANT P = 20000.
      CONSTANT Vdci = 1100.
      CONSTANT delta_Ves = 5.

END   !"of initial

DYNAMIC

TERMT(t.ge.tstop, 'Termination on time limit')

      DERIVATIVE

      P_star = P + 180000.*STEP(0.5) - 180000.*STEP(3.0)

      delta_ir = INTEG(-(delta_Vdci/Le)-(Re*delta_ir)/Le+delta_Ves/Le,0)

      delta_Vdci = INTEG(delta_ir/Ce+(P_star*delta_Vdci)/(Ce*Vdci**2),5)


      END.  !"of derivative"

END   !"of dynamic"

END   !"of program"
```

D. LINEAR .CMD FILE

```
!"simplelin.cmd"
!"Greg Greseth - 8 April 1999"

!"This file plots the linearized inductor current and capacitor"
!"voltage for the simplified DC link model"

s strplt = .t.                 ! "one variable per x-axis"
s calplt = .f.

s devplt = 1                   ! "1 for X-windows"
                         ! "5 for postscript"

s ppoplt = .f.                 ! "true rotates plot 90 deg"

s xinspl = 6                   ! "x-axis plot units"

s weditg = .f.                 ! "false suppresses data write"
                         ! "each time SCHEDULE occurs"
s wesitg = .f.

s nrwitg = .f.                 ! "true enables accumulation of data"
                         ! "after a CONTIN"

s alcplt = .f.                   ! "false makes all plots dark"
```

```
prepare t,delta_ir,delta_Vdci

PROCED linear
      start
            plot delta_ir,delta_Vdci
        END
```

APPENDIX D: FILTER-CONVERTER ACSL MODEL

A. .CSL FILE

```
!"hardsw.csl"
!"written by John Ciezki"
!"modified by Greg Greseth - 29 April 1999"
!"last modified - 1 May 1999"

!"This models a DC-DC converter (buck chopper) with an DC link filter
at"
!"the input."


PROGRAM

INITIAL

      MAXTERVAL maxt = 2.0e-7      !"maximum integration step size"
        MINTERVAL mint = 1.0e-7

      CINTERVAL cint = 1.0e-3      !"data communication interval"
      ALGORITHM ialg = 5           !"integration algorithm"
                               !"4--R.K. 2nd, 5--R.K. 4th"
      NSTEPS    nstp = 1
        CONSTANT tstop = 0.25        !"stop point for integration"


      !"Buck Parameters"
      CONSTANT Lbuck = 1.0e-3        !"main inductance"
      CONSTANT Rlser = 0.0           !"Lbuck series resistance"
      CONSTANT Vdidrop = 0.0         !"diode forw conduction drop"
      CONSTANT Vswdrop = 0.0         !"switch forward drop"
      CONSTANT Cbuck = 2.0e-3        !"main output capacitance"
      CONSTANT Tramp = 250.0e-6      !"switching period (4kHz)"

      !"-----define and initialize the main switch conduction status"
      LOGICAL sw
      sw = .false.       !"T sw conducts, F sw blocks"

      !"-----define and initialize variable which keeps track of"
      !"      whether the converter is in contin or discontin mode"
      LOGICAL contmode
      contmode = .true.

      !"link filter parameters"
      CONSTANT Cf = 8265.0e-6        !"filter capacitance"
      CONSTANT Lf = 0.5e-3           !"filter inductance"
      CONSTANT Rs = 0.01             !"source resistance"

      !"state variable initial conditions"
      CONSTANT iLic = 0.0      !"Buck inductor current"
```

```
      CONSTANT Voic = 0.0       !"Buck output voltage"
      CONSTANT Vcfic = 1100.0 !"filter output voltage"
      CONSTANT iLfic = 0.0      !"filter inductor current"

      !"Load Parameters"
      CONSTANT Rmax = 4.5125          !"100% load"
      CONSTANT Rmin = 45.125          !"min load"

      !"start-up"
      CONSTANT trampup = 0.1          !"time to ramp from 0 to vrefmax"
      CONSTANT vrefmax = 950.0        !"max ref output voltage"
      LOGICAL rampon
      rampon = .TRUE.

      !"define the input voltage"
      CONSTANT Vin = 1100.0

END    !"of initial"

DYNAMIC

      TERMT (t .GE. (tstop-0.5*cint))

  DERIVATIVE
      !"Set the load resistance"
      Rload = Rmax

      SCHEDULE rampoff .XP. t-trampup
      IF (rampon) THEN
            Vref = Vrefmax*t/trampup
      ELSE
            Vref = Vrefmax
      ENDIF

      !"BUCK MODELING EQUATIONS"
      "------determine conduction status of sw1"
      PROCEDURAL(sw,isw=reframp,duty,iL)
            IF (duty .LE. reframp) THEN
                  sw = .false.   !"switch open"
                  isw = 0.0      !"source current zero"
            ELSE
                  sw = .true.    !"switch closed"
                  isw = iL
            ENDIF
      END         !"of procedural"

      "-----given conduction status of sw and whether current is"
      "     continuous or not, establish derivative of iL"
      PROCEDURAL(piL=sw,contmode,Vcf,Vo,iL,isw)

            !"----if sw gated, assume can conduct pos current"
            IF (sw) THEN
                  contmode = .true.
               piL = (-Rlser*iL+Vcf-Vswdrop-Vo)/Lbuck
            ELSE
                  "----if iL GT zero, diode conducts"
                  IF (contmode) THEN
```

```
                piL = (-Rlser*iL-Vdidrop-Vo)/Lbuck
              ELSE
                piL = 0.0 !"discontinuous mode"
              ENDIF
        ENDIF
    END          !"of procedural"

    !"link filter state variables integrated"
    Vcf = INTEG((iLf-isw)/Cf, Vcfic)
    iLf = INTEG((Vin-Vcf-(Rs*iLf))/Lf, iLfic)

    !"establish the derivative of Buck output voltage"
    pVo = (iL - io)/Cbuck

    !"integrate the state variables"
    iLub = INTEG(piL, iLic)
    iL = BOUND(-1.0e-6, 1.0e6, iLub)
    io = Vo/Rload
    Vo = INTEG(pVo, Voic)

    "----form the reference ramp waveform (0 to 1)"
    tt = mod(t, Tramp)
    reframp = tt/Tramp

    "-----schedule discontinuous mode when iL tries go neg"
    SCHEDULE DCM .XN. iL

    !"Control Algorithm for Buck"
    CONSTANT hv = 0.00914
    !CONSTANT hi = -0.003299
    CONSTANT hi = -0.003208
    CONSTANT hn = 6.093

    CONSTANT nic = 0.0           !"integral of volt err"
    CONSTANT intbnd = 1000.0
    CONSTANT minduty = 0.0
    CONSTANT maxduty = 0.99
    CONSTANT Kscv = 1.000        !"scale factor for voltage sensor"
    CONSTANT Ksci = 1.000        !"scale factor for current sensor"
    va = Vref-Vo                 !"proportional voltage term"
    ioave = Ksci*io
    iLave = Ksci*iL
    ia = iLave-ioave             !"proportional current term"

    pn = va
    nub = INTEG(pn, nic)         !"integral voltage term"
    n = BOUND(-intbnd, intbnd, nub)
    dss = Vref/Vin
    dub =dss + Kscv*hv*va + Ksci*hi*ia + Kscv*hn*n
    duty = BOUND(minduty, maxduty, dub)

END  ! "of derivative"

    vout = Rload*io
    "----establish transition to discontinuous mode Buck"
    DISCRETE DCM
          contmode = .false.
```

```
      END            !"of dcm"

      DISCRETE rampoff
            rampon = .FALSE.
      END

END  ! "of dynamic"

END  ! "of program"
```

B. .CMD FILE

```
!"hardsw.cmd"

!"Greg Greseth - 1 May 1999"
!"This file plots the output for a filter-converter model"

s strplt = .t.                ! "one variable per x-axis"
s calplt = .f.

s devplt = 1                  ! "1 for X-windows"
                        ! "5 for postscript"

s ppoplt = .f.                ! "true rotates plot 90 deg"

s xinspl = 6                  ! "x-axis plot units"

s weditg = .f.                ! "false suppresses data write"
                        ! "each time SCHEDULE occurs"
s wesitg = .f.

s nrwitg = .f.                ! "true enables accumulation of data"
                        ! "after a CONTIN"

s alcplt = .f.                  ! "false makes all plots dark"

prepare t,Vcf,iLf,iL,io,Vo,duty

PROCED startup
      s ialg=5
      s maxt=1.0e-6
      s cint=5.0e-4
      start
        s plt = 1
      plot Vcf,iLf,duty
        s plt = 2
        plot iL,io,Vo
END
```

APPENDIX E: MATLAB CODE FOR IMPEDANCE CALCULATIONS

A. HARD SWITCHING MODEL

```
%  findxferhard.m
%
%  Greg Greseth - 30 March 99
%            modified 19 April 99
%
%  This program will find the transfer function for a linearized buck
model
%  in order to determine T2 and T3 for the hard switching case.  For
analysis
%  purposes, delta Vref is assumed to be 0.
%

%  define the constants

Pin = 200e3;
Vrefo = 950;             % =Vout
Vino = 1100;
do = 0.8636;
L = 1e-3;
C = 2e-3;
R = 45.125;        % =Rcrit
initdeltaVin = 5;
K1 = -Vrefo/(Vino)^2;
ilo = Pin/Vino;

%  characteristic equation coeffiecients

d2 = 3639.5;
d1 = 5526354.8;
d_zero = 3351129059.4;

%  calculate the gains

hv = ((L*C)/Vino)*(d1-(1/(L*C)));    %hv = 0.00914;
hn = (d_zero*L*C)/Vino;              %hn = 6.093;
hi = -(L/Vino)*(d2-(1/(R*C)));             %hi = 0.003299;

T1num = [hi*C, hv, hn];

%  Define the A matrix

A = [(Vino*hi)/L,(-1/L)-(Vino*hv)/L-(Vino*hi)/(R*L),(Vino*hn)/L;...
      1/C,-1/(R*C),0;...
      0,-1,0];

%  Define the B matrix

B = [-Vrefo/(L*Vino)+do/L;0;0];
```

```
% Define the D matrix, which is always 0

D = 0;

% Define C matrix in order to find T2

C_T2 = [1,0,0];

% Find the transfer function which will define T2

[T2num,T2den] = ss2tf(A,B,C_T2,D)

% Redefine C matrix in order to find T3

C_T3 = [0,1,0];

% Find the transfer function which will define T3

[T3num,T3den] = ss2tf(A,B,C_T3,D)

% Determine the Zin numerator

Zin_num_hard = [T2den, 0]

% Determine the parts of the Zin denomenator

part1 = [do*T2num, 0];

part2 = [ilo*K1*T3den, 0];

part3 = ilo*conv(T1num, T3num);

part3 = part3(1,2:6);

Zin_den_hard = part1+part2+part3
```

B. SOFT SWITCHING MODEL

```
% findxfersoft.m
%
% Greg Greseth - 30 March 99
%           modified 19 April 99
%
% This program will find the transfer function for a linearized buck
model
% in order to determine T2 and T3 for the soft switching case.  For
analysis
% purposes, delta Vref is assumed to be 0.
%

% define the constants

Pin = 200e3;
```

```
Vrefo = 950;              % =Vout
Vino = 1100;
do = 0.8636;
L = 200e-6;
C = 400e-6;
R = 45.125;         % =Rcrit
initdeltaVin = 5;
K1 = -Vrefo/(Vino)^2;
ilo = Pin/Vino;

%  characteristic equation coefficients

d2 = 7299;
d1 = 22194879.2;
d_zero = 27000116071.2;

%  calculate the gains

hv = ((L*C)/Vino)*(d1-(1/(L*C)));    %hv = 0.00070508;
hn = (d_zero*L*C)/Vino;              %hn = 1.9636;
hi = -(L/Vino)*(d2-(1/(R*C)));             %hi = 0.001317;

T1num = [hi*C, hv, hn];

%  Define the A matrix

A = [(Vino*hi)/L,(-1/L)-(Vino*hv)/L-(Vino*hi)/(R*L),(Vino*hn)/L;...
      1/C,-1/(R*C),0;...
      0,-1,0];

%  Define the B matrix

B = [-Vrefo/(L*Vino)+do/L;0;0];

%  Define the D matrix, which is always 0

D = 0;

%  Define C matrix in order to find T2

C_T2 = [1,0,0];

%  Find the transfer function which will define T2

[T2num,T2den] = ss2tf(A,B,C_T2,D)

%  Redefine C matrix in order to find T3

C_T3 = [0,1,0];

%  Find the transfer function which will define T3

[T3num,T3den] = ss2tf(A,B,C_T3,D)

%  Determine the Zin numerator

Zin_num_soft = [T2den, 0]
```

```
% Determine the parts of the Zin denomenator

part1 = [do*T2num, 0];

part2 = [ilo*K1*T3den, 0];

part3 = ilo*conv(T1num, T3num);

part3 = part3(1,2:6);

Zin_den_soft = part1+part2+part3
```

C. NYQUIST PLOT FILE

```
% stability.m
%
% Greg Greseth  -  19 April 99
%
% This program will find the Nyquist plot of the impedance ratio
% between the filter output impedance and the converter input
% impedance.  The desired result is to have the magnitude of the
% ratio be less than one over all range of angular frequency.

% Define the functions being analyzed:
% Zs is output impedance of the filter
% Zi is input impedance of the converter
% hard indicates values used for hard switching converter
% soft indicates values used for soft switching converter

% IMPORTANT !!!!!!!!!!!
% Both findxferhard.m and findxfersoft.m must be run with the desired
% converter values must be run first to ensure that the input
% impedance vectors are in the matlab variable list

% define the filter parameters and source resistance

Rs = 0.01;          % Source resistance
Cf = 6000e-6;             % Filter capacitance - 8265e-6
Lf = 0.5e-3;              % Filter inductance - 0.5e-3

% calculate the filter output impedance

Zsnum = [1/Cf, Rs/(Cf*Lf)];          % numerator
Zsden = [1, Rs/Lf, 1/(Cf*Lf)];             % denomenator

% calculate the hard switching ratio for Nyquist test

hardnum = conv(Zsnum,Zin_den_hard);
hardden = conv(Zsden,Zin_num_hard);

% calculate the soft switching ratio for Nyquist test

softnum = conv(Zsnum,Zin_den_soft);
```

```
softden = conv(Zsden,Zin_num_soft);

%  Nyquist plot for hard switching case

figure (1)
nyquist(hardnum,hardden)

%  Nyquist plot for soft switching case

figure (2)
nyquist(softnum,softden)
```

APPENDIX F: ACSL MODEL FOR LYAPUNOV-BASED STABILITY

A. .CSL FILE

```
PROGRAM              !"oneload.csl"

!"Greg Greseth - 13 May 1999"

!"This file finds the load current and load voltage for a single load
system"
!"for the Lyapunov-based stability analysis.  The non-linear system
equations"
!"for the simplified model are utilized.  The simulation event models a"
!"disturbance (drop) in the source voltage."

      INITIAL

            CONSTANT R=0.01                  !"resistance value"
            CONSTANT L1=0.0005               !"inductor 1 value"
            CONSTANT C1=.008265              !"capacitor 1 value"
            CONSTANT P1=200000.0             !"load 1 power"
            ALGORITHM ialg = 5               !"Runge-Kutta 4th order"
            CONSTANT tstop = 1.0             !"stop time for integration"
            NSTEPS nstp=1
            MAXTERVAL maxt = 1.0e-4          !"max integration step size"
            MINTERVAL mint = 1.0e-7          !"min integration step size"
            CINTERVAL cint = 4.0e-3          !"data communication interval"
            CONSTANT DROP = 55.0             !"source voltage disturbance"
            CONSTANT VDCSS = 1100.0          !"source voltage steady state"

      END   !"of initial"

      DYNAMIC

            DERIVATIVE

                  VDC=VDCSS-DROP*step(0.5)       !"supply voltage"

!"initial conditions"

                  CONSTANT I1IC=190.0
                  CONSTANT V1IC=1000.0

!"current"

                  I1=INTEG(-R/L1*(I1)-V1/L1+VDC/L1,I1IC)

!"conditions for V1"

                  IF(V1.LE.0.01) THEN
                        pV1=I1/C1
                  ELSE
```

```
                PV1=I1/C1-P1/(C1*V1)
          ENDIF

!"voltages"

          V1=INTEG(pV1,V1IC)

          TERMT(T .GE .TSTOP, 'Termination on time limit')

      END   !"of derivative"

   END   !"of dynamic"

END   !"of program"
```

B. .CMD FILE

```
!"oneload.cmd"
!"Greg Greseth - 13 May 1999"

!"This file plots the load current and load voltage for a single load
system"
!"for the Lyapunov-based stability analysis"

s strplt = .t.                    !"one variable per x-axis"
s calplt = .f.

s devplt = 1                      !"1 for x-windows"
                      !"5 for postscript"

prepare t, I1, V1

procedure plot1

    start
    plot I1 /xtag='time' /tag='Load 1 Current' V1 /tag='Load 1
Voltage'

end
```

APPENDIX G: ACSL MODEL FOR INTEGRATED SYSTEM

A. .CSL FILE

```
PROGRAM            !"system.csl"

            !"Greg Greseth, LT, USN  -  13 May 99"

            !"Last Revised  -  26 May 99

            !"This ACSL file simulates a reduced order model for a
synchronous"

            !"machine and three phase rectifier, with the output through
a DC"

            !"link filter and a buck chopper with a resistive load."

            !"Necessary inputs/known values are:"

            !"Output from the model is:"

      INITIAL            !"Section in which constants and program
parameters are defined"

            ALGORITHM ialg = 5                   !"Runge-Kutta 4th order"
            CONSTANT tstop = 0.25                !"stop time for
integration"
            MAXTERVAL maxt = 5.e-7               !"max integration step
size"
            MINTERVAL mint = 1.e-6               !"min integration step
size"
            CINTERVAL cint = 5.e-4               !"data communication
interval"

            CONSTANT wb = 377.
            CONSTANT rkqpri = 0.0613
            CONSTANT rkdpri = 0.24
            CONSTANT rfdpri = 0.00111
            CONSTANT J = 1.
            CONSTANT Tl = 1.
            CONSTANT B = 0.
            CONSTANT P = 2.                      !"number of poles"
            CONSTANT Xls = 0.08
            CONSTANT Xmq = 1.00
            CONSTANT Xlkqpri = 0.330
            CONSTANT Xmd = 1.77
            CONSTANT Xlfdpri = 0.137
            CONSTANT Xlkdpri = 0.334
            CONSTANT rs = 0.00515
            CONSTANT exfdo = 0.0042
            CONSTANT alfahat = 0.0
```

```
            CONSTANT PI = 3.141593
            CONSTANT rad120 = 2.094395
            CONSTANT rad60 = 1.047198
            CONSTANT rad30 = 0.523599
            CONSTANT Vpkstar = 1.654
            CONSTANT confact = 400.0
            CONSTANT sterm = 0.002

            u = 0.05    !"initialize u for use in first findu function
call"

            !"define the subtransient reactances"

            Xqpripri = Xls+(Xmq*Xlkqpri)/(Xlkqpri+Xmq)
            Xdpripri =
Xls+(Xmd*Xlfdpri*Xlkdpri)/(Xmd*Xlfdpri+Xmd*Xlkdpri&
+Xlkdpri*Xlfdpri)

      !"Buck Parameters"
      CONSTANT Lbuck = 1.0e-3       !"main inductance"
      CONSTANT Rlser = 0.0          !"Lbuck series resistance"
      CONSTANT Vdidrop = 0.0        !"diode forw conduction drop"
      CONSTANT Vswdrop = 0.0        !"switch forward drop"
      CONSTANT Cbuck = 2.0e-3       !"main output capacitance"
      CONSTANT Tramp = 250.0e-6     !"switching period (4kHz)"

      !"-----define and initialize the main switch conduction status"
      LOGICAL sw
      sw = .false.      !"T sw conducts, F sw blocks"

      !"-----define and initialize variable which keeps track of"
      !"      whether the converter is in contin or discontin mode"
      LOGICAL contmode
      contmode = .true.

      !"link filter parameters"
      CONSTANT Cf = 8265.0e-6       !"filter capacitance"
      CONSTANT Lf = 0.5e-3          !"filter inductance"
      CONSTANT Rsrc = 0.01          !"source resistance"

      !"state variable initial conditions"
      CONSTANT iLic = 0.0     !"Buck inductor current"
      CONSTANT Voic = 0.0     !"Buck output voltage"
      CONSTANT Vcfic = 1100.0 !"filter output voltage"
      CONSTANT iLfic = 0.0    !"filter inductor current"

      !"Load Parameters"
      CONSTANT Rmax = 4.5125        !"100% load"
      CONSTANT Rmin = 45.125        !"min load"

      !"start-up"
      CONSTANT trampup = 0.1        !"time to ramp from 0 to vrefmax"
      CONSTANT vrefmax = 950.0      !"max ref output voltage"
      LOGICAL rampon
      rampon = .TRUE.

      !"scale between per unit values and actual values"
```

```
      CONSTANT currscal = 202.0
      CONSTANT voltscal = 411.0

            COMMON / forsub /
rad30,rad60,rad120,Xqpripri,Xdpripri,PI,currscal


      END           !"of initial section"

      DYNAMIC

            TERMT(t.ge.(tstop-0.5*cint), 'Termination on time limit')

            DERIVATIVE

                  !"equations included for field voltage control of the
generator"

                  Vfdpri = (exfd*rfdpri)/Xmd

                  Vpk = sqrt(Vqsr*Vqsr+Vdsr*Vdsr)

                  Vdiff = Vpkstar - Vpk

                  exfdub = confact*realpl(sterm,Vdiff,exfdo)

                  exfd = BOUND (-7.0, 7.0, exfdub)

                  !"state equations for psikqpri, psikdpri, psifdpri, wr
and thetar"

                  psikqpri = INTEG(-wb*rkqpri*ikqpri, -0.120)

                  psikdpri = INTEG(-wb*rkdpri*ikdpri, 1.647)

                  psifdpri = INTEG(-wb*rfdpri*ifdpri+wb*Vfdpri, 1.777)

                  !"wrm = INTEG(((1./J)*(Te-Tl-B*wrm)), 0.)"

                        !"relationship between wrm and state wr

                        !"wr = (P/2.)*wrm"
                        wr = 377.

                  thetar = INTEG(wr, 0.)

                  !"thetar = mod(theta,rad60) + rad60d"

                  !"electrical torque equation"

                  !"Te = ((3./P)/(4.*wb))*(psidsr*iqsr-psiqsr*idsr)"
                  Te = psidsr*iqsr-psiqsr*idsr

                  !"solve first for ikdpri, ifdpri and ikqpri"

                  ikdpri = (1./((Xlkdpri+Xmd)*(Xlfdpri+Xmd)-
Xmd**2.))*((Xlfdpri+Xmd)&
```

```
*(psikdpri-Xmd*idsr)-Xmd*(psifdpri-Xmd*idsr))

                    ifdpri = (1./((Xlkdpri+Xmd)*(Xlfdpri+Xmd)-Xmd**2.))*(-
Xmd*(psikdpri&
-Xmd*idsr)+(Xlkdpri+Xmd)*(psifdpri-Xmd*idsr))

                    ikqpri = psikqpri/(Xlkqpri+Xmq)-
(Xmq*iqsr)/(Xlkqpri+Xmq)

                    !"equations to eliminate psiqsr and psidsr"

                    psiqsr = Xqpripri*iqsr+psiqpripri

                    psidsr = Xdpripri*idsr+psidpripri

                    !"define the subtransient flux linkages"

                    psiqpripri = (Xmq/(Xmq+Xlkqpri))*psikqpri

                    psidpripri =
((Xmd*psikdpri)/Xlkdpri+(Xmd*psifdpri)/Xlfdpri)&
/(1.+Xmd/Xlfdpri+Xmd/Xlkdpri)

                    !"define Eqpripri and Edpripri"

                    Eqpripri = (wr*psidpripri)/wb

                    Edpripri = -(wr*psiqpripri)/wb

                    !"define phi to use to determine alpha"

                    phi = ATAN2(Edpripri,Eqpripri)

                    !"call function to determine beta"

                           beta =
findbeta(psidpripri,psiqpripri,iLf,alfahat)

                    !"define alpha"

                    alpha = beta - phi

                    !"desired reduced order voltage-behind-reactance
equations"

                    Vqsr = rs*iqsr+(wr/wb)*Xdpripri*idsr+Eqpripri

                    Vdsr = rs*idsr-(wr/wb)*Xqpripri*iqsr+Edpripri

                    !"equation for average DC voltage out of rectifier"

                    Vdc = (3.*sqrt(3.)/PI)*(wr/wb)*(sqrt(psiqpripri**2&
+psidpripri**2))*(cos(alpha))-(3./PI)*(wr/wb)*(((Xqpripri+Xdpripri)/2.)&
*(iLf/currscal)+(Xdpripri-Xqpripri)*(iLf/currscal)*sin(2.*beta+rad30))

                    !"need to define K1 for use in subroutines"
```

```
                    Kone = sqrt(3.)*(-
psiqpripri*sin(beta)+psidpripri*cos(beta))&
+((Xdpripri-Xqpripri)*cos(2.*beta+rad120)-0.5*(Xqpripri+Xdpripri))&
*(iLf/currscal)

                    !"call function to determine u using 'half-it' method"

                    u = findu(Kone,psiqpripri,psidpripri)

                    !"now with the new u, we can determine conduction
currents"

                    iqsrcond = ((2.*sqrt(3.))/PI)*(iLf/currscal)&
*(cos(beta+rad120)-cos(beta+u+rad60))

                    idsrcond = ((2.*sqrt(3.))/PI)*(iLf/currscal)&
*(sin(beta+rad120)-sin(beta+u+rad60))

                    !"calculate the commutating currents using Simpson
method"

                    !"first, define the 5 different values of thetar to be
used"

                    thetar1 = beta+rad60

                    thetar2 = beta+rad60+u/4.

                    thetar3 = beta+rad60+u/2.

                    thetar4 = beta+rad60+(3.*u)/4.

                    thetar5 = beta+rad60+u

                    !"call each q and d subroutine 5 times to calculate
components"

                    PROCEDURAL (Q1 =
thetar1,Kone,psiqpripri,psidpripri,iLf)

                          CALL
simpsonq(thetar1,Kone,psiqpripri,psidpripri,iLf,Q1)

                    END   !"of procedural"

                    PROCEDURAL (D1 =
thetar1,Kone,psiqpripri,psidpripri,iLf)

                          CALL
simpsond(thetar1,Kone,psiqpripri,psidpripri,iLf,D1)

                    END   !"of procedural"

                    PROCEDURAL (Q2 =
thetar2,Kone,psiqpripri,psidpripri,iLf)
```

```
CALL
simpsonq(thetar2,Kone,psiqpripri,psidpripri,iLf,Q2)

END  !"of procedural"

PROCEDURAL (D2 =
thetar2,Kone,psiqpripri,psidpripri,iLf)

CALL
simpsond(thetar2,Kone,psiqpripri,psidpripri,iLf,D2)

END  !"of procedural"

PROCEDURAL (Q3 =
thetar3,Kone,psiqpripri,psidpripri,iLf)

CALL
simpsonq(thetar3,Kone,psiqpripri,psidpripri,iLf,Q3)

END  !"of procedural"

PROCEDURAL (D3 =
thetar3,Kone,psiqpripri,psidpripri,iLf)

CALL
simpsond(thetar3,Kone,psiqpripri,psidpripri,iLf,D3)

END  !"of procedural"

PROCEDURAL (Q4 =
thetar4,Kone,psiqpripri,psidpripri,iLf)

CALL
simpsonq(thetar4,Kone,psiqpripri,psidpripri,iLf,Q4)

END  !"of procedural"

PROCEDURAL (D4 =
thetar4,Kone,psiqpripri,psidpripri,iLf)

CALL
simpsond(thetar4,Kone,psiqpripri,psidpripri,iLf,D4)

END  !"of procedural"

PROCEDURAL (Q5 =
thetar5,Kone,psiqpripri,psidpripri,iLf)

CALL
simpsonq(thetar5,Kone,psiqpripri,psidpripri,iLf,Q5)

END  !"of procedural"

PROCEDURAL (D5 =
thetar5,Kone,psiqpripri,psidpripri,iLf)
```

```
                        CALL
simpsond(thetar5,Kone,psiqpripri,psidpripri,iLf,D5)

                  END   !"of procedural"

                  !"now add all the components together"

                  iqsrcom = (u/(PI*4.))*(Q1+4.*Q2+2.*Q3+4.*Q4+Q5)

                  idsrcom = (u/(PI*4.))*(D1+4.*D2+2.*D3+4.*D4+D5)

                  !"add the commutating and conduction components to get
average"
                  !"iqsr and idsr"

                  iqsr = iqsrcom+iqsrcond

                  idsr = idsrcom+idsrcond

      !"Set the load resistance"
      Rload = Rmax

      SCHEDULE rampoff .XP. t-trampup
      IF (rampon) THEN
            Vref = Vrefmax*t/trampup
      ELSE
            Vref = Vrefmax
      ENDIF

      !"BUCK MODELING EQUATIONS"
      "------determine conduction status of sw1"
      PROCEDURAL(sw,isw=reframp,duty,iL)
            IF (duty .LE. reframp) THEN
                  sw = .false.  !"switch open"
                  isw = 0.0     !"source current zero"
            ELSE
                  sw = .true.   !"switch closed"
                  isw = iL
            ENDIF
      END         !"of procedural"

      "-----given conduction status of sw and whether current is"
      "     continuous or not, establish derivative of iL"
      PROCEDURAL(piL=sw,contmode,Vcf,Vo,iL,isw)

            !"----if sw gated, assume can conduct pos current"
            IF (sw) THEN
                  contmode = .true.
               piL = (-Rlser*iL+Vcf-Vswdrop-Vo)/Lbuck
            ELSE
                  "----if iL GT zero, diode conducts"
                  IF (contmode) THEN
                    piL = (-Rlser*iL-Vdidrop-Vo)/Lbuck
                  ELSE
                    piL = 0.0 !"discontinuous mode"
                  ENDIF
            ENDIF
```

```
END          !"of procedural"

!"link filter state variables integrated"
Vcf = INTEG((iLf-isw)/Cf, Vcfic)
iLf = INTEG((Vdc*voltscal-Vcf-(Rsrc*iLf))/Lf, iLfic)

!"establish the derivative of Buck output voltage"
pVo = (iL - io)/Cbuck

!"integrate the state variables"
iLub = INTEG(piL, iLic)
iL = BOUND(-1.0e-6, 1.0e6, iLub)
io = Vo/Rload
Vo = INTEG(pVo, Voic)

"----form the reference ramp waveform (0 to 1)"
tt = mod(t, Tramp)
reframp = tt/Tramp

"-----schedule discontinuous mode when iL tries go neg"
SCHEDULE DCM .XN. iL

!"Control Algorithm for Buck"
CONSTANT hv = 0.00914
!CONSTANT hi = -0.003299
CONSTANT hi = -0.003208
CONSTANT hn = 6.093

CONSTANT nic = 0.0            !"integral of volt err"
CONSTANT intbnd = 1000.0
CONSTANT minduty = 0.0
CONSTANT maxduty = 0.99
CONSTANT Kscv = 1.000         !"scale factor for voltage sensor"
CONSTANT Ksci = 1.000         !"scale factor for current sensor"
va = Vref-Vo                  !"proportional voltage term"
ioave = Ksci*io
iLave = Ksci*iL
ia = iLave-ioave              !"proportional current term"

pn = va
nub = INTEG(pn, nic)          !"integral voltage term"
n = BOUND(-intbnd, intbnd, nub)
dss = Vref/Vcf
dub =dss + Kscv*hv*va + Ksci*hi*ia + Kscv*hn*n
duty = BOUND(minduty, maxduty, dub)

      END   !"of derivative"

vout = Rload*io
"----establish transition to discontinuous mode Buck"
DISCRETE DCM
      contmode = .false.
END           !"of dcm"

DISCRETE rampoff
      rampon = .FALSE.
END
```

```
      END   !"of dynamic"

END   !"of program"
      SUBROUTINE simpsonq(thetarsimp,Kone,psiqpripri,psidpripri,iLf
     +                          ,iqsrout)
***********************************************************************
*
* subroutine to calculate components for simpson method of determining
* the q commutating currents
*
***********************************************************************
      COMMON / forsub / rad30,rad60,rad120,Xqpripri,Xdpripri,PI,
     +                  currscal
*
* declare variables
*
      real ias, part1, part2, part3, Kone, iqsrout, iLf, currscal
*
* break the equation for ias down into manageable parts
*
      part1=Kone-sqrt(3.)*(psiqpripri*cos(thetarsimp+rad30)+psidpripri
     +      *sin(thetarsimp+rad30))
*
      part2=(Xqpripri-Xdpripri)*cos(2.*thetarsimp+rad60)+Xqpripri
     +      +Xdpripri
*
      part3=((Xqpripri-Xdpripri)*cos(2.*thetarsimp+rad120)+0.5
     +      *(Xqpripri+Xdpripri))*(iLf/currscal)
*
* combine the 3 parts to determine ias
*
      ias=(part1/part2)-(part3/part2)
*
* now solve for iqsr at the inputed thetar
*
      iqsrout=((2.*sqrt(3.))/3.)*(ias*cos(thetarsimp+rad30)-
     +        (iLf/currscal)*sin(thetarsimp))
*
      end
      SUBROUTINE simpsond(thetarsimp,Kone,psiqpripri,psidpripri,iLf
     +                          ,idsrout)
***********************************************************************
*
* subroutine to calculate components for simpson method of determining
* the d commutating currents
*
***********************************************************************
      COMMON / forsub / rad30,rad60,rad120,Xqpripri,Xdpripri,PI,
     +                  currscal
*
* declare variables
*
      real ias, part1, part2, part3, Kone, idsrout, iLf, currscal
*
* break the equation for ias down into manageable parts
*
```

```
      part1=Kone-sqrt(3.)*(psiqpripri*cos(thetarsimp+rad30)+psidpripri
     +       *sin(thetarsimp+rad30))
*
      part2=(Xqpripri-Xdpripri)*cos(2.*thetarsimp+rad60)+Xqpripri
     +       +Xdpripri
*
      part3=((Xqpripri-Xdpripri)*cos(2.*thetarsimp+rad120)+0.5
     +       *(Xqpripri+Xdpripri))*(iLf/currscal)
*
* combine the 3 parts to determine ias
*
      ias=(part1/part2)-(part3/part2)
*
* now solve for idsr at the inputed thetar
*
      idsrout=((2.*sqrt(3.))/3.)*(ias*sin(thetarsimp+rad30)+
     +         (iLf/currscal)*cos(thetarsimp))
*
      end
      REAL FUNCTION findu(Kone,psiqpripri,psidpripri,iLf)
************************************************************************
*
* function subprogram to calculate u using the 'half-it' method
*
************************************************************************
      COMMON / forsub / rad30,rad60,rad120,Xqpripri,Xdpripri,PI,
     +                  currscal
*
* declare variables to be used
*
      logical condition
      real utemp, fcom, fpricom, Kone, iLf, u1, u2, u, currscal
*
      u1=0.0
      u2=rad60
      u=0.0
      fcom=Kone-sqrt(3.)*(-psiqpripri*sin(beta+u)+psidpripri
     +     *cos(beta+u))-((Xqpripri-Xdpripri)*cos(2.*beta+2.*u
     +     -rad120)+0.5*(Xqpripri+Xdpripri))*(iLf/currscal)
10    if (ABS(u1-u2) .gt. 0.001) then
         u = 0.5*(u1+u2)
         fcom=Kone-sqrt(3.)*(-psiqpripri*sin(beta+u)+psidpripri
     +        *cos(beta+u))-((Xqpripri-Xdpripri)*cos(2.*beta+2.*u
     +        -rad120)+0.5*(Xqpripri+Xdpripri))*(iLf/currscal)
         if (fcom .le. 0.00) then
            u1=u
         else
            u2=u
         endif
         goto 10
      endif
      findu=u
      END
      REAL FUNCTION findbeta(psidpripri,psiqpripri,iLf, alfahat)
************************************************************************
*
* function subprogram to calculate beta
```

```
*
**********************************************************************
      COMMON / forsub / rad30,rad60,rad120,Xqpripri,Xdpripri,PI,
     +                  currscal
*
* declare variables to be used
*
      real betatop, betabot, betamin, alfahat, fbmin, iLf, currscal
*
      betatop = PI
      betabot = -PI
      betamin = 0.0
*
* calculate the function to determine if beta is greater than betamin
*
      fbmin = SQRT(3.)*(psiqpripri*cos(betamin)+psidpripri*sin(betamin))
     +        +2.*(iLf/currscal)*(Xqpripri-Xdpripri)
     +        *sin(2.*betamin-rad60)
10    if (ABS(betatop-betabot) .gt. 0.001) then
         betamin = (betatop+betabot)/2.
         fbmin = SQRT(3.)*(psiqpripri*cos(betamin)+psidpripri
     +        *sin(betamin))+2.*(iLf/currscal)*(Xqpripri-Xdpripri)
     +        *sin(2.*betamin-rad60)
         if (fbmin .le. 0.0) then
            betabot = betamin
         else
            betatop = betamin
         endif
         goto 10
      endif
*
* now determine beta based on the above determination
*
      findbeta = alfahat + betamin
      END
```

B. .CMD FILE

```
s strplt = .t.              ! "one variable per x-axis"
s calplt = .f.

s devplt = 1                ! "1 for X-windows"
                      ! "5 for postscript"

s ppoplt = .f.              ! "true rotates plot 90 deg"

s xinspl = 6                ! "x-axis plot units"

s weditg = .f.              ! "false suppresses data write"
                      ! "each time SCHEDULE occurs"
s wesitg = .f.

s nrwitg = .f.              ! "true enables accumulation of data"
```

```
                              ! "after a CONTIN"
s alcplt = .f.                          ! "false makes all plots dark"

s tstop = 1.0

s maxt=5.0e-7

s cint=1.0e-3


prepare
t,Vdc,Te,psikqpri,psikdpri,psifdpri,iqsr,idsr,u,thetar,beta,alpha,phi&
        Vcf,iLf,duty,Vo,io,exfd

! "runs a start up to 100%, downpower to 10%, and uppower to 100%"

PROCED runsystem
      s tstop = 0.5
      start
      s cint = 1e-4
      s devplt = 5
      s plt = 1
      plot /xlo=0.0 /xhi=0.5 Vdc,Vcf,Vo
      s plt = 2
      plot /xlo=0.0 /xhi=0.5 iLf,io
      s plt = 1
      plot /xlo=0.0 /xhi=0.5 Vdc,Vcf,Vo
      s plt = 2
      plot /xlo=0.0 /xhi=0.5 iLf,io
      s devplt = 1
      s tstop = 0.52
      contin
      s nrwitg = .t.
      s Rmax = 45.125
      s tstop = 0.57
      contin
      s Rmax = 4.5125
      s tstop = 0.62
      contin
      s devplt = 5
      s plt = 4
      plot /xlo=0.5 /xhi=0.62 Vdc,Vcf,Vo
      s plt = 10
      plot /xlo=0.5 /xhi=0.62 iLf,io
      s plt = 4
      plot /xlo=0.5 /xhi=0.62 Vdc,Vcf,Vo
      s plt = 10
      plot /xlo=0.5 /xhi=0.62 iLf,io
      s devplt = 1
      s nrwitg = .f.
      s tstop = 0.65
      contin
      s tstop = 0.67
      s Cf = 400e-6
      contin
      s nrwitg = .t.
```

```
      s Rmax = 45.125
      s tstop = 0.72
      contin
      s Rmax = 4.5125
      s tstop = 0.77
      contin
      s plt = 13
      s devplt = 5
      plot /xlo=0.65 /xhi=0.77 Vdc,Vcf,Vo
      s plt = 14
      plot /xlo=0.65 /xhi=0.77 iLf,io
      s plt = 13
      plot /xlo=0.65 /xhi=0.77 Vdc,Vcf,Vo
      s plt = 14
      plot /xlo=0.65 /xhi=0.77 iLf,io

END

!"runs a start up to 10%, uppower to 100% and downpower to 10%"

PROCED runsystem2
      s tstop = 0.5
      s Rmax = 45.125
      start
      s cint = 1e-4
      s devplt = 5
      s plt = 14
      plot /xlo=0.0 /xhi=0.5 Vdc,Vcf,Vo
      s plt = 15
      plot /xlo=0.0 /xhi=0.5 iLf,io
      s plt = 14
      plot /xlo=0.0 /xhi=0.5 Vdc,Vcf,Vo
      s plt = 15
      plot /xlo=0.0 /xhi=0.5 iLf,io
      s devplt = 1
      s tstop = 0.52
      contin
      s nrwitg = .t.
      s Rmax = 4.5125
      s tstop = 0.57
      contin
      s Rmax = 45.125
      s tstop = 0.62
      contin
      s devplt = 5
      s plt = 16
      plot /xlo=0.5 /xhi=0.62 Vdc,Vcf,Vo
      s plt = 17
      plot /xlo=0.5 /xhi=0.62 iLf,io
      s plt = 16
      plot /xlo=0.5 /xhi=0.62 Vdc,Vcf,Vo
      s plt = 17
      plot /xlo=0.5 /xhi=0.62 iLf,io
      s devplt = 1
      s nrwitg = .f.
      s tstop = 0.65
      contin
```

```
s tstop = 0.67
s Cf = 400e-6
contin
s nrwitg = .t.
s Rmax = 4.5125
s tstop = 0.72
contin
s Rmax = 45.125
s tstop = 0.77
contin
s plt = 18
s devplt = 5
plot /xlo=0.65 /xhi=0.77 Vdc,Vcf,Vo
s plt = 19
plot /xlo=0.65 /xhi=0.77 iLf,io
s plt = 18
plot /xlo=0.65 /xhi=0.77 Vdc,Vcf,Vo
s plt = 19
plot /xlo=0.65 /xhi=0.77 iLf,io
```

END

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